Noncontact Injuries in Scottish Hockey: A Study of Epidemiology, Current Practice and a Preventative Measure

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Dedication

This thesis is dedicated to my family. My mother, who has always supported me. My father, Mr Alan Johnston, who sadly passed away during my PhD studies after a battle with cancer. He will always be a source of inspiration and I hope I achieve as much as him in his quiet, selfless yet determined manner. My wife, for her continued love and support and our child (due in May 2021) who, I hope, will be proud of my achievement.

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Finally, thank you to my family for their support and grounding through this process. To my parents and grandparents for their support both emotional and financial without which, I could not have completed this work. Last, but not least, to my now wife, whom I met at the start of my studies. Kirsty – thank you for your patience, support and most importantly, your love.

Abstract

Introduction: There is limited evidence on noncontact injury epidemiology, current warm-up practice and exercise interventions used to reduce injuries in hockey. Therefore, the aims of this thesis are to investigate (1) noncontact injuries, (2) current warm-up practice and (3) the effects of a novel warm-up on female sub-elite hockey players in Scotland.

Methodology: Study 1 was an online injury survey on 317 hockey players focussing on noncontact injuries. Study 2 was an observational study that investigated the current warm-up practices of 17 hockey teams. Study 3 was a controlled study that used 40 female hockey players and explored the effects of an 8-week hockey-specific neuromuscular training programme (NMTP) on electromyography, kinematics and kinetics during a sagittal plane hop, hop and twist and unanticipated sidecut.

Results: Study 1 showed that the most common injuries were affecting the knee and hamstrings (0.89 and 0.69/1000 hours respectively) with no timeloss (31.4%) or mild to moderate injuries (30.3%) and usually occurred during sidecutting, sudden acceleration and landing (19.6%, 13.8% and 12.9% respectively). The injuries were more frequently occurring to females than males 4.73 vs 3.47/1000 hours. Study 2 revealed a warm-up time of 20 minutes including pulse raiser, activate and mobilise and potentiate elements. The occurrence of static stretching was greater (41.2%) than neuromuscular training (11.7%). Study 3 showed some significant increases in muscle activation for Gastrocnemius, Quadriceps and Gluteals both pre-and post-landing, with greater increases in the intervention group. There were significant reductions in maximum knee abduction, excursion and the rate of force development following 8-weeks of neuromuscular training. There were no significant differences in performance.

Conclusion: Noncontact hockey injury epidemiology requires further research and the current provision of warm-ups should be evidence-based. A novel hockey-specific NMTP can elicit some significant changes in muscle activity, kinematics and kinetics that may reduce the risk of noncontact injuries.

Keywords: Hockey, noncontact, injury, neuromuscular training, warm-up

Chapter One: Introduction

1.1 Background

Field hockey (which from hereon in is called ‘hockey’) is an ancient game, a popular game, an Olympic sport that is played across the world by both men and women (Federation of International Hockey (FIH) n.d). It is a physically demanding sport in which players cover up to 10km per game (White & MacFarlane, 2013). At the recreational level, it is played over two, 35-minute periods; at the elite level, it follows a slightly different format (4 x 15 mins). The rules of hockey are structured to reduce the risk of contact, via stick, ball or player, and to minimise injury including any dangerous play. These rules show that hockey is a non-contact sport (FIH, 2016, p.23 section 9) that requires safe distances to be retained between opposing teams at certain times.

Hockey has been studied extensively over the last 50 years (Podgórski & Pawlak, 2011) through time-motion analysis, notational analysis and studies of injuries and warm-ups. Warm-ups are defined as “techniques used to increase local muscle and core body temperature prior to vigorous exercise. Can be either active or passive and may be specific to the sport or exercise about to be performed” (Brooker, 2008, p.514). Likewise, injuries, in general, have been extensively investigated; whether in a community setting (Stevenson et al., 2000a), in the National Collegiate Athletic Association (NCAA) (Dick et al., 2007), in junior and senior elite competition (Junge et al, 2006; Rishiraj et al., 2008; Theilen et al., 2016). All studies suggest that injuries occur frequently, mostly to the lower extremity via contact with a stick, ball or another player. The percentage of non-contact injuries has been reported to be up to 64% of all injuries (Delfino et al., 2018); however, the variation is considerable amongst studies. Also, the level of detail regarding non-contact injuries and the quantity of information that is available is very limited (Barboza et al., 2019). Therefore, due to this variability of findings amongst studies and limited details, further research is required.

Those who participate in exercise should perform warm-ups to prepare for the upcoming exercise session (Bishop, 2003b, 2003a). This process is focused on raising the temperature of muscles; yet many studies have shown that a temperature increase is not necessarily the only benefit of the warm-up process (Fradkin e al., 2006; Alikhajeh et al., 2012). Muscle activation and technique changes that can be practised during warm-ups and may help to reduce the risk of injuries and to improve performance have been shown to be additional benefits of neuromuscular training (NMT) (Hopper et al., 2017; Weir et al., 2019; Zebis et al., 2016). Despite the possible benefits of warm-ups, both in terms of injury reduction and the theoretical performance benefits, the published data on the current practice of warm-ups in sport are limited. A study of golfers suggests that this population rarely performs warm-ups (Fradkin et al., 2001). There has been some insights into warm up practice in football (Towlson et al., 2013) and mentioned briefly by Steele (1990) referring to veteran hockey players. To the author's knowledge, only one study has investigated warm-ups in hockey in detail (Avest, 2010). The findings suggest that the practice is varied; static stretching is frequently used. In addition, there is some evidence that coaches would like more time for their players to perform warm-ups. Therefore, further research is warranted into the current practices of warming up in hockey teams in Scotland and to explore the perceptions of coaches regarding the warm-up and use of NMT.

NMT, in contrast to warm-ups, is defined as "training enhancing unconscious motor responses by stimulating both afferent signals and central mechanisms responsible for dynamic joint control" (Risberg et al., 2001, p620). NMT programmes have been used as a means to reduce the risk of injury in team sports (Delfino et al., 2019; Hislop et al., 2017; Soligard et al., 2008; Weir et al., 2019). Also, the frequency of occurrence of specific injuries, for example, anterior cruciate ligament (ACL) injuries, can be reduced by up to 70% (Grindstaff et al., 2006). A reduction in the number of ACL injuries was reported among elite female hockey players after the introduction of a biomechanically informed NMT programme (Weir et al., 2019). This may be due to a reduction in knee valgus, especially in these high-risk athletes whose use of the NMT regime reduced knee valgus by 30% and improved their muscle activation strategies. This study also showed improvements in performance. This investigation found that high-risk athletes had significantly decreased peak knee valgus and greater lower extremity muscle activation. Barboza et al. (2019) showed also a reduction in the number of injuries among youth players of both genders and all levels who undertook a NMT programme.

The studies reported above suggest that injury rates can be reduced through use of NMT among both elite female players (Weir et al., 2019) and mixed 10–17-year-old players (Barboza et al., 2019). The evidence also suggests that elite female players improve their muscle activation strategies (in this case, by 30% in their mean gluteal total muscle activation) and kinematics (high-risk athletes reduced their peak knee valgus by 30%) following intensive NMT (Weir et al., 2019).

The pertinent factors that influence the effects of NMT are the age of participants, the exercise dosage, exercise variation, delivery mode and compliance rate among the athletes (Leppänen et al., 2014). A meta-analysis by Sugimoto et al. (2016) indicated that the greatest benefits of NMT were accrued among early teen participants (< 14 years old) who undertook the programme for 20 minutes at least twice per week during the season, performing multiple modes of exercise and receiving verbal feedback. Further, the prophylactic effect was greatest with a compliance rate of 66% or greater (Sugimoto et al., 2014).

There is no evidence to date to explore the effects of a NMT programme on the biomechanics of recreational-level female hockey players. Therefore, part of the work conducted for this thesis endeavoured to fill this gap in the evidence base.

Therefore, the main aims of this work conducted for this thesis were to investigate:-

1. non-contact injuries in Scottish hockey; the nature, severity and mechanisms of these injuries and the characteristics of those who sustain them (Study 1).

2. current practice and coaches' perceptions of the warm-up in hockey in Scotland (Study 2); and

3. the biomechanical effects of a NMT programme on female hockey players (Study 3).

This thesis is organised in the following way. Chapter Two contains the literature review and provides a narrative approach to enable the reader to understand the research that has been performed to date. It includes a review of pertinent areas that relate to: injury and warm-up definitions, epidemiology of injuries in team sports; anatomical and biomechanical characteristics of injury, risk factors, mechanisms of injury, warm-ups, finally some methodological considerations and specific aims and objectives of this thesis. Chapter Three focuses on the first study, which established the injury epidemiology of hockey players in Scotland. Chapter Four details study two, which investigated current warm-up practice in both genders across all leagues in Scotland. Chapter Five draws together findings from studies one and two and investigates the effects of a novel NMT among female hockey players and compares these findings with a control group. Chapter Six brings together and discusses the overall findings of the three studies, offers recommendations for practitioners and further research and finally presents the overall conclusions of this thesis.

The research adopts a materialistic ontological position for all three studies. Carswell-Smart (2020) states that materialism in philosophy takes the view that "all facts (including facts about the human mind and will and the course of human history) are causally dependent upon physical processes". Using this approach, study one examined the injuries that were sustained by each hockey player, who also completed a questionnaire (Appendix 3.1). The findings from study two included details of the observed warm-up processes and additional data that were taken from the questionnaires. Findings from study three were informed from the electromyography (EMG), kinematic, and kinetic data of three tasks. Furthermore, the researcher used rationalism as the epistemological position. Rationalism can be described as knowledge derived through reasoning (Thomas et al., 2011) and the doctrine that knowledge about reality can be obtained by reason alone without recourse to experience the doctrine that human knowledge can be all encompassed within a single, usually deductive, system (Collins Dictionary, 2007). This approach formed the basis of studies one and three and informed the development of the questionnaire that was used in study two. In study three, empiricism was used in the first instance followed by rationalism once the data had been analysed. Empiricism has been described as practice based on experiment and the observational view that all concepts originate in experience (Oxford English Dictionary, 1993) and that knowledge is gained through experiment and observation (Thomas et al., 2011)

Chapter Two: Literature review

2.1 Background

Hockey is an intensive, intermittent, invasive sport that involves many repeated actions in a variety of directions and planes (McManus et al., 2007). The nature of the sport leads to injuries that occur as a result of contact with a stick, ball or other players, or an injury may occur without contact (non-contact). Most injuries occur to the lower extremities; however, few studies have reported the frequency, nature, severity or mechanisms of development of non-contact injuries, especially among female players (Dick et al., 2007; Delfino Barbosa et al., 2018; Rees et al., 2020). As there are no sport-specific agreed definitions, a number of operational definitions have been developed.

2.2 Operational definitions

Injury definitions vary within the literature with no agreed definition in hockey (Barboza et al., 2019). Finch (1997) and van Mechelen (1997) reviewed definitions that were in use and confirmed that, during sporting activities, a wide variety of injuries were contracted that resulted in physical damage and required players to attend hospital for treatment. The National Collegiate Athletic Association (NCAA) of the US set up an injury surveillance system (ISS) in 1982. The NCAA defines an injury as a soreness that requires medical attention by a qualified doctor or physiotherapist and prevents the athlete from participating in the sport for at least one day (Dick et al., 2007). However, in a systematic review of knee injuries among adolescents, Louw et al. (2008) reported that, even in high-quality studies, six definitions were in use. However, four studies out of the final 16 that were selected for the review (Bergstrøm et al., 2001; Elias, 2001; Jones et al., 2000; Pasque & Hewett, 2000) did not state what definition had been used.

There have been attempts to gain a consensus regarding the definition of injuries in individual sports. Fuller et al. (2007) define an injury as

> *"any physical complaint, caused by a transfer of energy that exceeds the body's ability to maintain its structure and/or functional integrity, that was sustained by a player during a rugby match or rugby training, irrespective of the need for medical attention or time loss from sports activities"* (p178).

Time loss refers to the period that an athlete or player does not partake fully in training or competition. More recently, Timpka et al. (2014) have published a definition of injury in athletics, which is largely based on work by Fuller et al. (2007), Alonso et al. (2010) and Engebretsen et al. (2010a) as:

> *"a physical complaint or observable damage to body tissue produced by the transfer of energy experienced or sustained by an athlete during participation in athletics training or competition, regardless of whether it received medical attention or its consequences with respect to impairments in connection with competition or training"* (Timpka et al., 2014, p484).

In the same year, Drew et al. (2014) defined an injury for the Australian Institute of Sport as

> *''any physical or medical complaint that results in an athlete being unable to participate in training or competition, as planned by coaching staff, for greater than 24h" (p.e25)*

The variations in injury definition could complicate the comparison of evidence that is reported for different studies. For this thesis, the definition that was presented by Fuller et al. (2007) is used, since it is the most frequently used and accepted definition, and it is practical and non-clinical.

2.2.1 Injury classification

To accurately record and report injury data, classification systems have been developed and definitions of injuries have been provided. These classification systems categorise injuries by use of a code for each injury, body part and injury type. This information can be used to form a database of injury occurrence and severity. The Orchard injury classification system (OSICS – 10) that was proposed by Rae and Orchard (2007) was developed from a wide injury and disease perspective and was adapted for use to classify sports injuries. More specifically in sport, the NCAA ISS (Dick et al., 2007) developed a community-based reporting method, which uses a short message service (SMS) (Ekegren et al., 2014) to report injuries. The system has been evaluated as valid by the developers; however, it has yet to be validated further within large-scale studies (Møller et al., 2018).

All systems, no matter how comprehensive, are subject to reliability issues (Finch et al., 2014; Hammond et al., 2009). The data collection method detailed above that uses SMS requires that medical professionals compile the data, and this requirement limits the quantity of information that can be collected. Furthermore, the categorisation process includes the mechanism of injury, such as player contact, no contact or other contact (Hootman et al., 2007; Junge et al., 2008). This classification is particularly pertinent when the information is used in injury prevention studies.

2.2.2 Injury severity

As in the cases of the definitions of injury, various definitions are related to injury severity. These range from the nature of the injury through the length of time lost from the sport to the financial cost of the injury (Fuller, 2007). The consensus statement that was developed by Fuller et al. (2006; 2007), define injury severity in terms of the time lost from the sport, i.e. the number of days that pass from the occurrence of the injury to the player's return to full participation. The consensus definition is described as practical and non-clinical (Fuller, 2007). A limitation to the definition is that not all players return to their sport fully recovered and/or take part completely in all activities.

Further ambiguity surrounds the categorisation of the severity of the injury. In rugby, an injury that leads to a day lost is defined as of slight severity; one that leads to two to three days out is of minimal severity; four days, mild; 21 days lost, moderate; an injury that leads to more than a month lost is 'severe'; and one that lays the player up for longer is defined as career threatening (Fuller et al., 2007). In athletics, a minor injury is defined as one that lasts for one to seven days; moderately serious is one that lasts for eight to 28 days; a serious injury takes from 28 days to six months for recovery, and long term is > six months) (Timpka et al., 2014). Whereas this method defines as minor an injury that incurs a time out of seven days, Louw et al. (2008) classify injuries that require this period of time out as mild. Classification of severe injuries conflicts similarly; one study quotes a time loss of three weeks (Yang et al., 2005) while another quotes four weeks (Junge et al., 2000). The measure of severity and its variability in the assessment of consequential time loss is recognised by Dick et al., (2007). As a result, the NCAA ISS authors (Dick et al., 2007) decided to record only injuries that restricted participation for 10 or more days. The method of classification of injury severity requires further clarity and consistent use between studies to enable data comparison (Rae & Orchard, 2007). Severity data in this thesis will be measured in terms of the number of days during which the player could not play (lost days) and the categorisation followed the definition suggested by Fuller et al. (2007).

2.2.3 Recurring injuries

Recurring injuries are also called repeat, recurrent, exacerbated, subsequent or multiple injuries in the literature and these terms are often used interchangeably (C. F. Finch & Cook, 2013). Some studies have investigated this category of injury in some detail (Finch and Cook, 2013; Fuller et al., 2007). As with the other injury classification systems, the choice of definition has an impact on data collection and interpretation. Finch and Cook (2013) report that the application of their subsequent injury categorisation (SIC) model to existing data increases the numbers of injuries that are classified as subsequent. This model facilitates a greater understanding of subsequent injuries; however, the classification requires independent evaluation and validation.

Fuller et al. (2007) describe a ‘subsequent’ injury as repeated, sustained damage that follows complete recovery from a previous injury. Therefore, they define it as “an injury of the same type and same site that occurs after a player’s return to full participation from the index injury” (Fuller et al., 2007, p178). In this thesis, the Fuller definition is used and the data are examined with respect to injuries that involve time loss.

2.2.4 Non-contact injury definition

It is important that researchers have an agreed definition of a ‘non-contact injury’, as the definition influences the calculations of injury rates and validates the conclusions of a study, such as in an intervention-based investigation (Pfeiffer et al., 2006). However, agreement is lacking even in a well-researched area such as knee injuries (Krosshaug et al., 2005a; Myer et al., 2007; Marshall et al., 2010; Gilchrist et al., 2008) define non-contact injuries as “an anterior cruciate ligament [ACL] injury sustained by an athlete without extrinsic contact by another player or object on the field’’ (p.1478). In contrast, Marshall (2010) defines non-contact injuries as those that occur in scenarios that lack external force. These injuries include those that arise from the athlete's own movements and Dick et al. (2007b) define non-contact injuries as those that occur with "no apparent contact" (p.177). The definition that is used in this thesis is similar to that proposed by Junge et al. (2008), which states that a non-contact injury is "a traumatic event without contact with another athlete or object" (p. 415). This is because this definition takes into account other epidemiological research, has previously been used in a hockey setting and contains the necessary elements consistent with the sport.

2.2.5 Recording of injuries and injury rates

Several measurement units are cited within the injury literature. The most commonly used classification is the number of injuries per 1000 hours of play (e.g. Delfino et al., 2018; Ekstrand et al., 2011). Other researchers have used the classifications of the number of injuries per 1000 athletic-exposures (AEs) (e.g. Dick et al., 2007), the number of injuries per athlete per year (Karen Murtaugh, 2009) or the rate of injury per 10,000 player minutes (Hopkins et al., 2007). Hodgson (2000) demonstrates how the reporting format can distort the conclusions of a study. The author uses the analogy of rugby injuries that are sustained over two seasons, which appear to have the same rate (approximately 150). However, once the number of hours played is considered, the injury rate in 1996 is almost double that of 1993/4 (Hodgson, 2000). The classification that states injury rate per 1000 hours is recommended by Hodgson (2000). Therefore, in this thesis the number of injuries per 1000 player hours.

2.2.6 Summary – definitions

There are numerous definitions regarding the characteristics of an injury. These are the severity and type of injury and the unit of measurement to report the injury rate. The definition of each term that is used in this study is specified. The epidemiology of hockey injuries is discussed later in this chapter with a focus on non-contact injuries. The next section examines the events that cause injury (e.g. sidestepping, known as 'cutting', and landing) and the methods that can mitigate this type of injury, such as the warm-up intervention.

2.3 Injury models

Of the injury prevention programmes that have been implemented, most have used the framework proposed by van Mechelen et al. (1987) as cited in van Mechelen et al. (1992). This commonly cited, four-stage model outlines an approach to injury prevention and forms the basis of related research and the foundation of other models. This model is described as efficient by Tiggelen et al. (2008). The four stages and the order of their implementation are shown below (Figure 2.1). This is a logical approach if a little simplistic. Bahr and Kroshaug (2005) discuss that identifying and the risk factors and the mechanisms of injury are not always apparent (Figure 2.3).

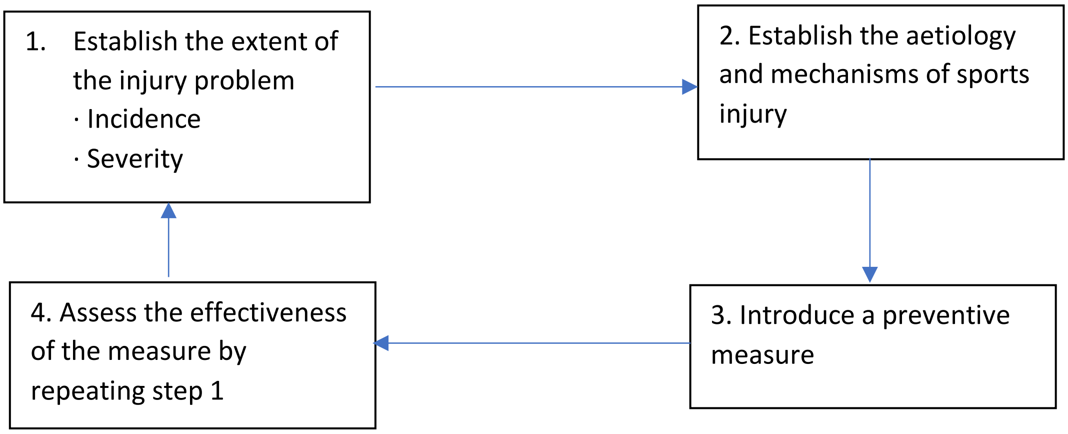

Figure 2. 1 Four-step sequence of injury prevention programmes (van Mechelen et al., 1987, cited in van Mechelen et al., 1992).

Other studies have expanded on this model. Finch (2006) added two stages in between van Mechelen’s stages 3 and 4. The translating research into injury prevention practice (TRIPP) model explains that there is a need to research implementation issues and to evaluate injury prevention programmes scientifically as well as to examine injury surveillance and aetiology and the mechanisms by which injuries are contracted. Scientific evaluation of preventative measures may reduce some of the inaccuracies that are associated with recall bias (Schmier & Halpern, 2004).

Bahr and Krosshaug (2005) outline some practical guidelines for the conduct of injury prevention research, which align with the work of van Mechelen. The logical steps that are required to discover the extent of the issue under investigation are: the establishment of the incidence and severity of the injury (Step 1), followed by an investigation of the aetiology (cause or causes) and mechanism/s of injury (Step 2). This approach may lead to the introduction of preventative measures, which may include rule changes; use of more protective equipment; and/or use of a NMT programme. The cyclical model leads back into step 1 as any changes in the sport may lead to other, different or new injuries.

To understand the risk for each athlete more comprehensively, a more encompassing model than that of van Mechelen et al. (Figure 2.2) was developed by Meeuwisse (1994). This model accounts for internal and external risk factors as well as their interaction. The event that may lead to an injury, or the mechanism of injury, is the final element in the overall risk assessment for each athlete. This model has been subsequently embellished by Bahr & Krosshaug (2005), who added more detail into the intrinsic risk factors (such as physical fitness levels), which are now termed internal risk factors. They also elaborated on the extrinsic risk factors (now referred to as external risk factors, such as environment) and the inciting event (such as player behaviour).

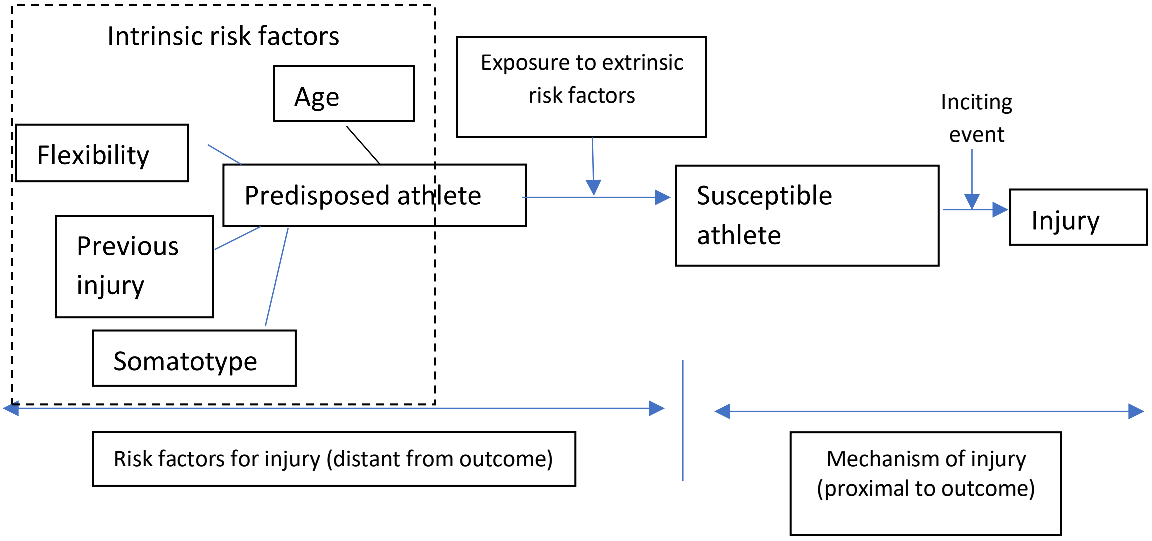

Figure 2. 2 Meeuwisse’s epidemiological model of injury

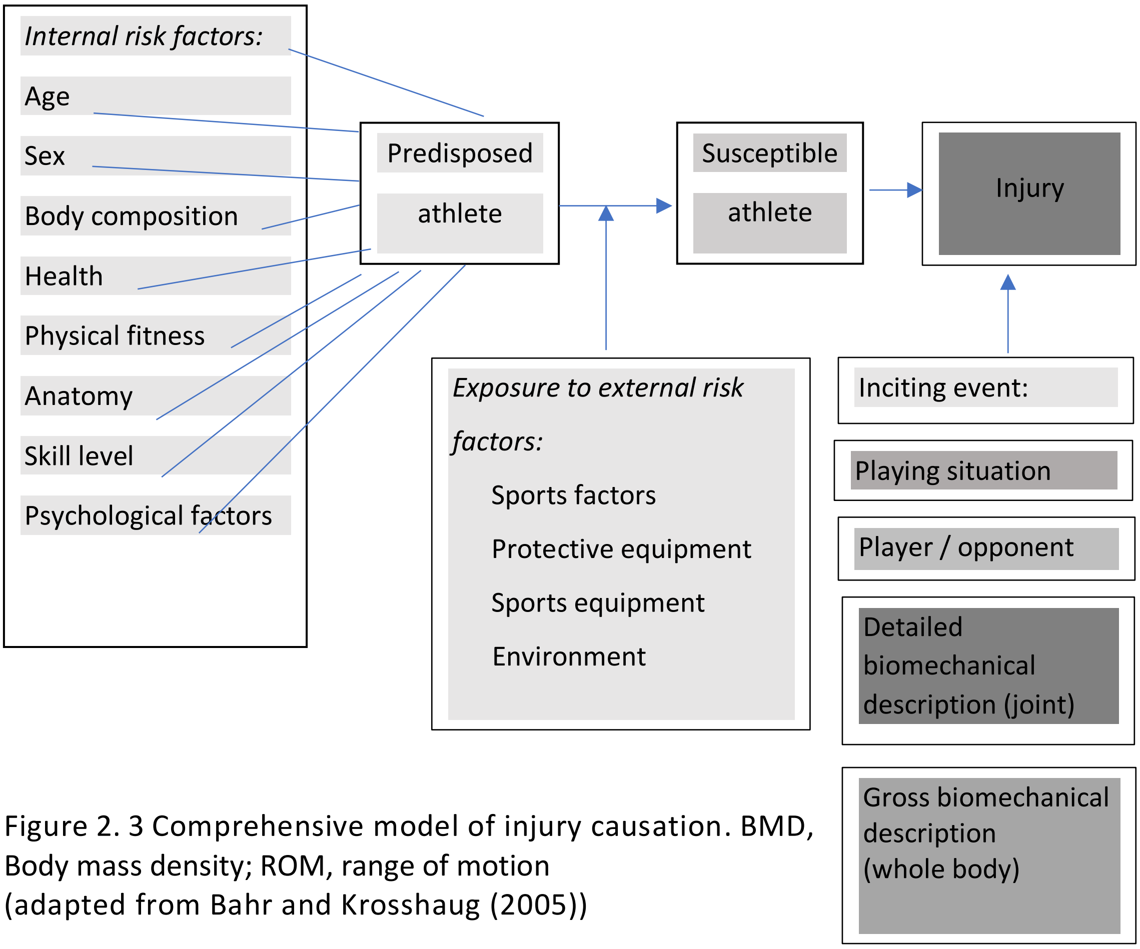

Figure 2. 3 Comprehensive model of injury causation. BMD, Body mass density; ROM, range of motion
(adapted from Bahr and Krosshaug (2005))

In both models that are shown above, the inciting event or injury mechanism is a key factor; a factor which Bahr and Krosshaug (2005) describe as not well defined. Whiting and Zernicke (1998) define it as "the fundamental physical process responsible for a given action" (p.298). McIntosh (2005) has proposed a model to provide a definition. The model focuses on a biomechanical approach that combines the interaction of load and load tolerance with other influential factors such as the supervision (coaching) of risk management, competitiveness and awareness of loads. This model is different from other proposed models in that it takes into account the multi-directional nature of injury prevention, the positive or negative influence of the load that is imposed by training and the ability of individuals to tolerate the demands of the training that is implemented by the coach.

Subsequent injury-prevention models have attempted to address the limitations of previous work. These limitations include the inflexibility of linear models (Fuller et al., 2012; Meeuwisse et al., 2007), or lack of practical steps (Padua et al., 2014; Roe et al., 2017). To be effective, O'Brien and Finch (2014) suggest that models should be context specific and include ‘real-world challenges’. Therefore, an injury-prevention model for a whole team would be more appropriate. A team-sport injury prevention model has been developed (O’Brien et al., 2019) and informed by previous models such as those derived by van Mechelen et al. (1992) and Finch (2006). This six-step cyclical model may help practitioners with three phases: (1) (Re) Evaluation, (2) Identification and (3) Intervention (Figure 2.4). The effectiveness of this model has yet to be assessed.

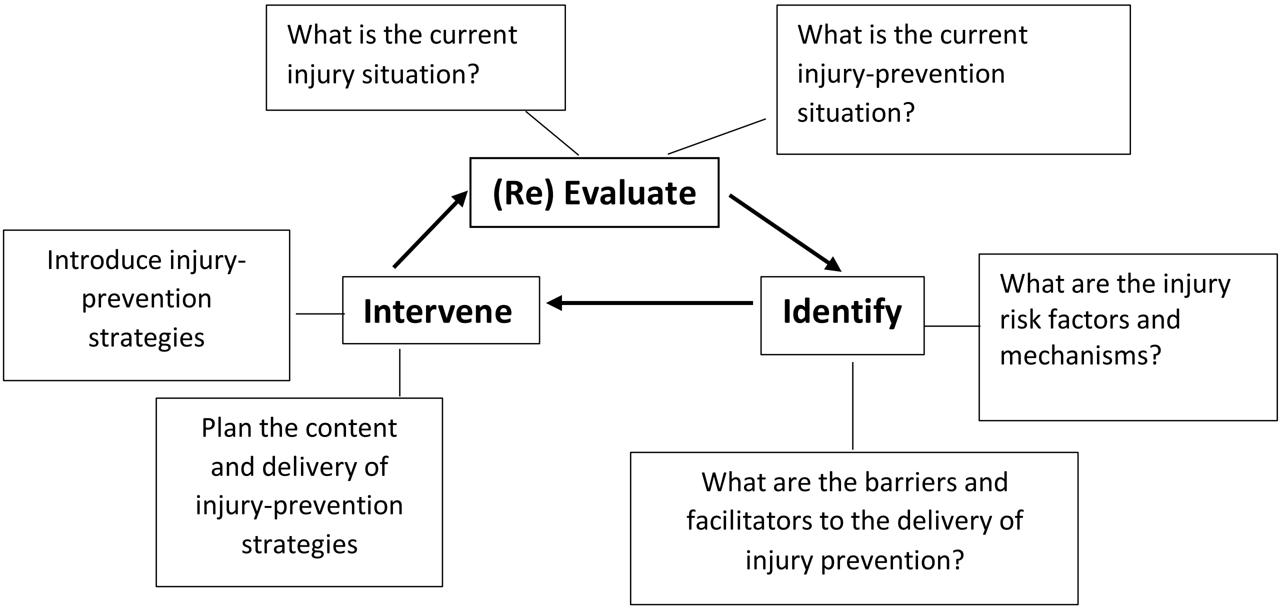

Figure 2. 4 The team-sport injury prevention (TIP) cycle (adapted from O’Brien et al., 2018)

The focus and scope of this thesis is to assess the extent of the non-contact injury problem (Steps 1 and 2 of van Mechelen’s model and O’Brien et al., 2018) within a highly susceptible population (see Meeuwisse, 1994) in order to provide an evaluated preventative measure - steps 3 and 4 of van Mechelen’s model, McIntosh (2005) and the intervene step of O’Brien et al., (2018). Equally, the data presented can provide sports scientists, coaches and athletes with education and increased understanding of non-contact injuries in hockey.

2.3.1 Principles of risk management, assessment and evaluation

There are frameworks for the management of risk in sport. Whilst there are multiple methods of risk assessment (e.g. Bahr and Holm, 2003), a four-step framework proposed by Fuller and Drawer (2004) was followed within this study. The four steps are the risk identification (through epidemiology), estimation (perceived or real and after preventative interventions), evaluation of (often after therapeutic interventions) and communication (to the relevant sporting community) regarding risk factors (Fuller & Drawer, 2004). Identification is of both internal and external risk factors. In the game of hockey, these include: the nature of the sport; equipment used (notably the stick and ball); and the structure of the goals. Risk estimation involves the identification of the consequences of the factors, with the inclusion of the magnitude and probability of injury occurrence. Epidemiological studies can provide evidence and therefore be used to inform accurately any necessary mitigation strategies. Risk estimation can be recorded on a scale of high to low, or as a figure, such as the number of injuries per 1000 hours. While risk is inherent within sport, no defined acceptable level of risk has been reported, yet governing bodies have a responsibility to manage the risks within their sports (Fuller & Drawer, 2004). The principles that were adopted in this study were the identification of risk factors and their estimation (steps 1 and 2 of van Mechelen's model).

Several alternative definitions and calculations of risk have been put forward by Fuller (2007) and Hopkins (2007). Risk can be defined as the expected lost playing time in a certain situation within a particular time period (Fuller, 2007). This is a function of the severity (how much time is lost) and incidence (how many events of this nature have occurred) within a specific time period. This can provide a good estimate of the risk of each type of injury.

2.3.2 Risk responsibility

Another element of risk in sport pertains to defining the fields of responsibility and implementation strategies that help to maximise the long-term safety of participants. Fuller (2007) discusses the ways in which involved governing bodies, teams and individuals have a responsibility to control and manage risk. Governing bodies can review the laws and regulations of their sports in light of the evidence that is available regarding injuries. For example, rules, equipment and/or officiating instructions can be altered to manage the risks effectively (for example, Gianotti et al., 2009). Logically, if changes are made within a sport, further research is required to assess the consequences of the new environment and to calculate the new level of risk (a stage in the TRIPP model (Finch, 2006)). Coaches can manage risks through the implementation of appropriate training regimes and practices that reduce the risk of injury. In professional sport, some coaches manage the risks by maintaining high numbers of members of a squad to counter the potential high injury rate so that they remain able to field a complete team, as coaches can only select from those who are listed as available (Fuller, 2007). Individuals and their behaviours can also influence the risks of injury. For example, the tackle technique that a football player chooses to use affects the probability of injury (Fuller et al., 2004).

2.3.3 Summary – injury models and risk management

The work described in this thesis followed the injury model described by van Mechelen (1987) and incorporated an element of the model described by Meeuwisse (1994). Study one investigated the risk factors and mechanisms of injury (stages 1 and 2). Study two investigated a current preventative measure, i.e. the warm-up. Finally, study three focused on the effects of a preventative measure; see stage 3 of the injury model developed by van Mechelen et al. (1987) and the TRIPP model proposed by Finch (2006) regarding the reduction of the number of intrinsic risk factors and the minimisation of the occurrence of inciting events.

2.4 Epidemiology of hockey injuries

2.4.1 Epidemiology definition

Epidemiology is "concerned with occurrence, transmission and control of epidemic diseases" (Collins Dictionary, 2007, 9th ed., p.651). In the context of sport and exercise, it is the investigation of many elements of the injury process, from attempts to predict the occurrence of injuries to the establishment of the frequency and mechanism of injuries and characteristics of the injured athletes. The nature of non-contact injuries that occur due to participation in intermittent, invasive team sports at all levels is discussed in this section.

2.4.2 Introduction to hockey injuries

There is a moderate amount of literature that reports the injuries that are likely to occur within the game of hockey. This section provides information pertaining to injury rates, which range from 0.1 to 90.9 per 1000 hours (Delfino et al., 2018), mechanisms by which injuries are created, and their severity and nature in hockey. Although several studies either have investigated team sports in general or have reported data from multi-sport events such as the Olympic Games, the majority have focused on injuries that have required hospital treatment, or in which the research has provided more general injury rate data from within a multi-team hockey competition. This section will cover injuries at all levels, from community or recreational hockey to elite-level play. A summary is provided in Appendix 2.0.

2.4.3 Injury rates at the elite level

At the elite level, injury rates in hockey fall at the higher end of the spectrum mentioned above; an injury rate of more than 44 per 1000 player hours have been documented, with evidence of a difference in rates between genders (29.1/1000 player hours for women and 48.3/1000 player hours for men) (Theilen et al., 2016). In a competitive context, it has been reported that an injury occurs in almost every match via contact between the ball and a lower extremity (Furlong & Rolle, 2017; Junge et al., 2006; Theilen et al., 2016). The rate of injury for both genders was reported to be similar at the 2012 Olympics (Engebretsen et al., 2013). In contrast, at the 2004 Olympics, the injury rate was greater (32 injuries per 1000 player hours) among male players (Junge et al., 2006). The comparable data from the 2016 Olympics are not available (Soligard et al., 2017). The injury rates may be due to the level of competition, and differences may be due to the prospective method of reporting and the diligence of the personnel involved, data from more competitions may be required for firmer conclusions to be made. However, the scale of the competition may limit the detail of the data, especially for non-contact injuries.

At the sub-elite level, Sharma et al. (2012) reported a greater percentage of injuries at the district level when compared with the incidence at higher levels in men’s hockey. However, this study did not report injury rates. In Dutch elite hockey, Barboza et al., (2019) reported that rates of development of acute new injuries were 3.5 per 1000 hours of training and 12.3 per 1000 hours in competition, with 74% of all injuries occurring by no contact.

At the NCAA level, injury rates are stated to be similar to those above at 10.8 per 1000 AEs. Dick et al. (2007) reported rates of injury that were incurred during practice and competition over a 15-year period; they found that women's field hockey injury rates were 21.2 and 15.0 per 1000 AEs in practice and competition respectively. Murtaugh (2009) reviewed hockey injury studies; however, the report does not include a description of a clear method with inclusion/exclusion criteria. This report demonstrated that a change of surface (grass or shale to sand-based /water-based artificial turf) and rules led to a change in the injury pattern. Murtaugh also reported that a synthetic surface increases chronic lower extremity injuries.

2.4.4 Community level injury rates

Across several team sports in a non-elite environment or at the community level (i.e. a similar population to the players who participated in this thesis) the injury rate was reported to be 16.7 per 1000 player hours (Stevenson et al., 2000). Hockey players were reported to sustain injuries at the rate of 15.2 per 1000 player hours (Finch et al., 2002; Stevenson et al., 2000). Within this population, Finch found that male players had a higher injury rate than female (19.0 vs. 12.3 per 1000 player hours). When players were grouped by age, the highest injury rate was reported to be in the 26-30-year-old group (21.2 per 1000 player hours), while the group that comprised players of 18 years and under showed the lowest injury rate (10.5 per 1000 player hours). The earlier research by Stevenson et al. (2000) reported similar injury rates. Neither study included data regarding the mechanism of injury or injury severity. Most recently, in a systematic review, Cornelissen et al. (2020) reported injury rates (time-loss only) in recreational youth players of 1.47 per 1000 AEs and an overall (time-loss and non-time-loss) injury rate of 9.82 per 1000 AEs. These figures were compared with injury rates among recreational adults of 5.19 per 1000 AEs for time-loss injuries and between 2.2 and 28.4 per 1000 AEs for non-time-loss injuries. In all the above studies, the exact injury rates and details regarding non-contact injuries in hockey were largely absent.

As a comparison, injury rates in other team sports are 73 and 70 per 1000 player hours in men's and women's football respectively, 89 and 145 per 1000 player hrs in men's and women's handball respectively and 96 and 1000 player hours in men's and women's basketball respectively (Junge et al., 2009).

2.4.5. Differences in injury rates according to gender and playing position

There is some uncertainty regarding which playing position is prone to the receipt of the most injuries. Murtaugh (2001) reported that goalkeepers were more likely to be injured than outfield players, whereas Dick et al. (2007) and Delfino et al. (2018) reported that midfielders received the most injuries and goalkeepers received the fewest. Sharma et al. (2012) found that forwards were more likely to be injured than defenders or midfield players. However, Rishiraj et al. (2009), who reported that players in the position of backs were more injured than those in other positions. These differences may be due to the role, tactics and style of play of the participants in each study.

It appears that male players are more likely to be injured than females (Murtaugh, 2009; Yard & Comstock, 2006). Junge et al. (2008) employed data from the 2004 Olympic Games, and Yard and Comstock (2006) reported emergency admission data; both sets of figures suggested that men received more injuries than women, and that male players were more likely to have a time-loss injury than females. This pattern is repeated in elite hockey, in which men have been found to be injured more often than women (48.3 vs. 29.1 respectively). The difference in the injury rates may be due to an increased number of contact injuries among male players, particularly in the areas close to the goal, and differences in performance of certain skills such as the drag flick. This action strains the body especially in the coronal plane (Bari et al., 2014) with a higher injury rate in those who perform this action (Ng et al., 2016)

2.4.6 Anatomical site of injuries

There is a lack of consensus amongst studies on the anatomical site that is most likely to be injured. Some studies show that lower limbs are injured most frequently, followed by the head and face. Of the lower extremities, ankles (especially ankle ligaments) are injured most frequently (Dick et al., 2007; Murtaugh, 2001; Naicker et al., 2007; Rishiraj et al., 2009) and account for approximately one-third of all injuries. Stevenson et al. (2000) and Finch et al. (2002) reported that the most injured body parts were finger/thumb (31.4%), knee (30.5%), thigh (30%) and ankle (28.1%), through bruising (79.5%), muscle damage (53.3%) and ligament damage (25.7%).

However, Sherker and Cassell (2002) used data on emergency admissions to hospital to report that injuries to the face and upper limbs were most common. Injury data from elite males also reported that the most frequent sites of injury were the face (18% approx.), ankle (13%), knee (10%) and shoulder (9%) (Sharma et al., 2012). Overall, however, despite minor variation, the majority of injuries were found to be to the lower extremities. In elite hockey, the prevalence of upper-body injuries appears to be greater.

Hootman et al. (2007) reported that field hockey exhibited lower rates of injury to knees and ankle ligaments than did other US college sports (ankle injuries numbered 0.43/1000 AEs in hockey vs. 0.83/1000 AEs overall and anterior cruciate ligament (ACL) injuries numbered 0.07/1000 AEs in hockey vs. 0.15/1000 AEs overall).

Lower-back injury is a common complaint among field hockey players (Murtaugh, 2001) as most ball-handling techniques involve spinal flexion and trunk rotation (Fenety and Kumar, 1992). These movements can also lead to spinal shrinkage (Reilly & Seaton, 1990). Further evidence of back malfunction was reported by Fenety and Kumar (1992), who found that hockey players who complained of pain in their backs exhibited a decreased lumbosacral range of motion and trunk strength compared with controls. The pain group also exhibited weaker eccentric trunk extension than the control group. The pain group showed stronger flexion, but this result was not statistically significant. In addition, Freke and Dalgliesh (1994) reported that 80% of female hockey players had lower-back dysfunction, whilst Murtaugh (2001) found that 59% of female hockey players reported lower-back pain of some kind. A more considered investigation by Haydt (2012) found that 56% of female hockey players had lower-back pain in the 2008 season, which is a similar figure to that reported by Murtaugh (2001). However, these authors compared the data with those of age-matched controls and found that 55% of the controls also reported lower-back pain. Pain in the lower back may be caused by increased trunk flexion with greater hip flexor moments (Braun et al., 2014; Smith et al., 2020). Despite the discussion above, the incidence of lower-back injury in all hockey positions is reported to be quite low; 2.1% of all injuries (Dick et al., 2007), 5.2% (Rishiraj et al., 2009), and 6.8% (Sharma et al., 2012).

In all studies, the detail of the injury aetiology, especially of non-contact injuries, is very limited.

2.4.7 The nature and severity of injuries

There is some consensus on the injuries that are sustained in hockey. Yard and Comstock (2006) reported injury data in children's hockey which showed that in both boys and girls, contusions (bruises) occurred most frequently, followed by sprains/strains. The third group of most frequently occurring injuries in boys were lacerations and in females, fractures. Dick et al. (2007) and Rishiraj et al. (2009) found that ligament strains/sprains to the ankles and knees were the most common injuries that were sustained in games, while in training, upper-leg strains, ankle-ligament strains and pelvis-hip injuries were the most common. All these injuries caused contusions and sprains followed by tendinopathy across all positions. The latter studies either did not report the injuries sustained or provided limited detail.

The ability to compare injury severity across studies is limited due to the variability in reporting methods and lack of reporting. The data below show that most of the injuries are mild; most time-loss injuries are reported to be of less than a week's duration and the overwhelming majority of time loss is less than one month.

Severe injuries, which are taken to be those that require 10+ days of time loss (Dick et al., 2007), accounted for 15% of game injuries and 13% of training injuries. Of the severe injuries, the knee was reported to be injured most frequently in games and training (23.1% and 15.3% respectively), followed by ankle-ligament sprains (9.1% in games and 8.2% in training). Most of these were non-contact injuries. Finger fractures in games (9.1%) and lower-leg fractures in training (9.7%) were the most common that involved bone breakages. Dick et al. (2007) reported that severe injuries to the knees and ankles were the most frequent non-contact injuries. However, no description of non-contact injuries was given.

2.4.9 Mechanism of injury

The mechanisms by which the injuries were sustained are reported sporadically. Of the data that are available, injuries due to contact with the ball or a stick are the most frequently reported. The other possible contact is with another player. Although hockey does not require player-to-player contact, it occurs often. The mechanism of non-contact injury is reported less frequently than the mechanism of contact injury; for instance, Junge et al. (2006) reported that 38% of all injuries were non-contact in nature, but the researchers gave no further details.

Sharma et al. (2012) reported the mechanisms or actions that led to injuries. However, in other studies, this information is very limited. Sharma et al. (2012) reported that 43.7% of injuries to male hockey players occurred during tackling; other hockey actions that led to injury included defending (33.3% of all injuries) and dribbling (20.2%). Sharma et al. (2012) suggested that greater investigation was required into the causes of injury among female players at the same levels for comparison.

2.4.10 Non-contact injuries in hockey

There is much variation in terms of reported incidence, which ranges from 12% to 64% (Delfino et al., 2018), and even to 74% (Barboza et al., 2018). Dick et al. (2007) reported that 27.6% of all injuries were of the non-contact type in matches, compared with 64% of injuries in training. Rishiraj et al. (2009) found that non-contact injuries were the most common (62%) of all injuries. The most prominent of these were muscle strains; ankle/foot, lower back and knee injuries occurred most frequently. Within the available literature, no association is made between mechanism, injury type and the anatomical site of the injury. Sharma et al. (2012) reported that non-contact injuries occurred less frequently than was found by Rishiraj et al. (2009). Among elite, male, Indian hockey players, non-contact injuries accounted for 20.5% of all injuries. Again, the detail of the injuries that were caused and the activity that was being performed when non-contact injuries were sustained was not reported in the study. Furthermore, in the studies by Murtaugh (2001), Yard and Comstock (2006) and Murtaugh (2009), non-contact data was not reported. Therefore, there is a need for further investigation of the frequency and mechanisms of non-contact injuries.

2.4.11 On-pitch location and timing of injuries

There is limited evidence regarding the pitch and its association with injuries. Dick et al. (2007) reported that players were injured most often inside the 25-yard (23-metre) line

(40.8%) or inside the circle (25.8%). These researchers assumed that players who were injured inside the 25-yard area were largely the victims of contact injuries. A similar pattern was found by Theilen et al. (2016), who found that half of all injuries occurred inside the circle and a third inside the 25-yard zone. The researchers' summary of the numbers of injuries that were sustained in each area of the pitch showed that more injuries occurred as players approached the goal, especially in the circle, where half of all the injuries occurred. Most injuries that were sustained in this area were contact injuries to the face/head (Theilen et al., 2016).

The timing of injuries within a hockey game has been reported in only a few studies. Theilen et al. (2016), who reported data from elite-level tournaments, showed that injuries occurred more frequently towards the end of each half period (mean 27.5% and 30.5% in second and fourth quarter respectively for both genders), and more occurred in the second half (54% and 68% for women and men respectively). A similar pattern was observed for women and men. This may be due to increased physical fatigue towards the end of the game, although this was not specified within the literature. Similar patterns were found by Rishiraj et al. (2009) and Nagle et al. (2017); Rishiraj et al. (2009) reported at least a four-fold increase in the injury rate during the second half of matches (27.7 per 1000 AEs (first half) vs. 107.3 per 1000 AEs (second half)) and training sessions (24.9 per 1000 AEs (first half) vs. 111.1 per 1000 AEs (second half)).

The timing of injuries appears to be consistent across studies, which have shown that injuries occur most frequently in the latter period of play. In football, it has been observed that the number of injuries gradually increases as the match progresses; approximately half of all match injuries occur between minutes 61 and 75 or within the last 15 minutes of the game (Ekstrand et al., 2009; Hawkins et al., 2001; Mohr et al., 2003; Woods et al., 2004). This may be due to the increase in distance that has been run, intensity and skills performance (Mohr et al., 2003; Rampinini et al., 2009), which lead to increased fatigue (Bangsbo et al., 2007). However, some studies suggest a much more even spread (Nagle et al., 2017). Nagle et al. found this evenness among sub-elite players; they considered that it may have been due to a decrease in the distance at which the players ran at high intensity during the final 15 minutes. In netball, researchers reported that players were injured during the middle section of each quarter and that more injuries (46.4%) occurred when players were attacking (Hopper et al., 1995). Langeveld et al. (2012) reported more injuries during the second and third quarters, followed by the fourth quarter (15.2%), with only 10% occurring in the first quarter. Handball (Bere et al., 2015) and Gaelic football (O'Connor et al., 2017) report a different pattern of slightly more injuries in the first half than the second (O'Connor et al., 2017). However, this pattern is not consistent (Langevoort et al., 2007).

2.4.12 Timing of injuries during a year/season

To the author's knowledge, only one hockey study has reported injury occurrence throughout the year (Finch et al., 2002). These data, collected over a two-year period, showed a fluctuation throughout the year (from 9.2 – 24.4 injuries per 1000 hours). However, more data are required as no clear pattern is evident. Hootman et al. (2007) reported that across 15 sports, including team and individual sports, over a one-year period, the numbers of game and practice injuries were quite consistent at 4/1000 AEs in practice and between 12/1000 AEs and 14/1000 AEs in games. Additionally, these researchers reported that pre-season injury rates were lower than in-season rates, and that post season was again slightly lower than in-season (6/1000 AEs, 14.5/1000 AEs and 8.7/1000 AEs respectively). This pattern could be a result of higher intensity play in competition than in training. However, only a few studies report these data; therefore, more longitudinal studies are needed to verify the findings.

Other team sports appear to show a similar pattern in the numbers of injuries that are sustained across a season. Studies in football indicate that the number of injuries peaks in October (first half of the season) and again in February (second half of the season) (Price et al., 2004; Woods et al., 2004). Hägglund et al. (2005) found that the numbers of injuries that were sustained during pre-season were significantly higher than at other times in the season. In contrast, at the elite club level, injuries appeared to occur at a more consistent rate across the season, and any reduction in the injury rates appeared to coincide with a reduction in playing time i.e. July into August and April into May (Ekstrand et al., 2009). This pattern was similar to that found in rugby (Brooks et al., 2005; Brooks et al., 2005b). A spike in injuries in the pre-season and early part of the season for recreation and sub-elite athletes may be due to the absence of conditioning in the offseason and a burst of training in the preseason whereas, elite athletes maintain a much greater level of fitness.

2.4.13 Age and level of Injury

Two studies (Stevenson et al., 2000; Finch et al., 2002) have considered the age effect on hockey injuries and show a clear trend. These prospective, five-month studies at community sports clubs showed that the injury frequency was dramatically greater among 18 – 25 year olds (43%) than in the 26 – 30-year-old age group (25%) and among older groups. These figures are similar to those of other team sports such as Australian rules football, basketball and netball (Finch et al., 2002; Stevenson et al., 2000). In football, Woods et al. (2004) reported that the numbers of injuries in the 17 – 22-year-old group were the highest and the rate fell as age increased. However, other studies contradict this trend. In a review of prospective studies on risk factors for lower extremity injuries, Murphy et al. (2003b) reported that six studies demonstrated an increased risk of injury with age, two studies indicated increased rates of injury among younger athletes and five studies reported no association between injury risk and age. However, as Murphy et al. discuss inter-study comparisons are difficult as there are several methods used, sports included and different age brackets used.

Data regarding injury rates according to the competition level of play indicate that higher rates of injury are reported at the lowest end of the performance spectrum (Sharma et al., 2012). This study reported that 31.4% of all injuries occurred at district level, 19.4% at university and 23% at national levels. The authors did not report how the university level compared with the others, and as only this one study reported this information, more investigation is required.

2.4.14 Summary – epidemiology

The epidemiological studies of hockey injuries suggest that injuries occur most frequently to the lower extremity and at a relatively even rate between genders and a slightly higher rate in the lower levels. Differences according to the position played on the field appear to be minimal, especially among the outfield positions. There are differences between age groups, as 18 – 25-year-olds sustain more injuries than players of other ages. The most frequent injuries are contusions, ligament sprains and strains and muscle strains caused by contact (with a player, stick or ball). On average, 38% of injuries are classified as non-contact, but there is little reported additional information. The severity of the injuries appears to be minimal; most injuries cause time losses of three days or fewer. The occurrence of injuries during sessions appears to be concentrated in the second half of both competitions and training periods. Furthermore, injuries seem to occur more frequently near the beginning of the season than at the end.

However, across all the research, the variation in the units of measurement limits the ability to compare data meaningfully. There is a lot of information about all injuries but limited detailed evidence of non-contact injuries. Therefore, an investigation into hockey injury epidemiology is warranted and is the focus of study one of this thesis.

2.5 External and internal risk factors

The risk of injury is inherent in most sports. However, there is a greater risk in some sports than in others. This section will briefly review the external (outside of the body, for example, shoe traction) and internal risk factors (such as gender and body composition), with the emphasis on specific factors that are most relevant to the work that is described in this thesis. These elements are part of the model proposed by Meeuwisse (1994).

2.5.1 External risk factors

Evidence suggests that the risk of injury in team sports is 6.16 vs. 2.88 per 1000 hours in individual sports (Theisen et al., 2013) and that team sports have a hazard ratio (injuries to the intervention group vs injuries to the control group) of 2.00 (Theilen et al., 2016). In hockey, the FIH warns that the game may include dangerous play but states that contact is prohibited. Hence hockey is classified as a non-contact sport (FIH, 2016, Section 9, p.23). Despite the non-contact rules, many injuries occur via contact with the stick, ball and/or the ground (Sherker & Cassell, 1998; Theilen et al., 2016). This contact appears to occur more frequently near the goal and during penalty corners (Theilen et al., 2016). During penalty corners, players are permitted to wear more protective equipment. In a number of sports, including hockey as played in Scotland, local rules have been implemented (amount of protective equipment worn by goalkeepers) for in an attempt to reduce the number of injuries that are sustained by youth players (Sherker & Cassell, 1998; Leaders Manual, Scottish Hockey, n.d.). Another factor affecting injury rates is rule obedience; 15% of injuries are due to foul play (Dvorak et al., 2011). It is interesting to note that initiatives in ice hockey, community sport and rugby to encourage respect for the rules and to promote fair play have had a positive effect (injury reduction)(Brunelle et al., 2005; Roberts et al., 1996; Timpka and Lindquist, 2001). Gianotti et al. (2009) reported that increased safe behaviour in contact situations led to a 4% decrease in injury rate overall.

The FIH states that major national and international competitions must be played on synthetic surfaces. This is also recommended at lower levels. As a result, most hockey is now played on synthetic surfaces that have replaced grass and blaze pitches and may have an effect as Sherker and Cassell (2002) reported harder surfaces increase injury rates.

2.5.2 Internal risk factors

Internal risk factors that predispose participants to injury include age (discussed earlier and part of the model by Bahr and Krosshaug, 2005), previous injury and muscle activation. Bahr and Holme (2003) also suggest that gender and joint motion are internal risk factors and these are discussed below.

2.5.3 Previous injury

It has been found that players with previous injuries show increased rates of subsequent injury, particularly to the same muscle group (Orchard, 2001). Arnason et al. (2004) found that the odds ratio for hamstring injuries was significantly higher (OR = 11.6, $p < 0.001$) and among those who had already had knee injuries (OR = 4.6) and that the risk of a new ankle sprain approached significance (OR = 5.3) for those who had previously had an ankle injury. Engebretsen et al. (2010), Van Beijsterveldt et al. (2012) and Freckleton and Pizzari (2013) found a similar trend in hamstring injuries. Engebretsen et al. (2010) found that the strongest factor (above age and playing position) for a new hamstring injury was a previous injury (OR = 2.62). This trend has been observed in youth football players, among whom almost 60% reported an injury history, and those who had an injury were twice as likely to get another. Those with two or more injuries were three times more likely to sustain another injury compared with those who reported no injury history (Kucera et al., 2005). This has been recognised by the American Medical Society for Sports Medicine (Difiori et al., 2014).

Several potential explanations have been presented as to why a previous injury increases the risk of re-injury. Injury can lead to proprioceptive deficits, including a decrease in the number of mechanoreceptors (Dhillon et al., 2012), that directly affect functional stability. An injury can also decrease muscle strength and may cause agonist-antagonist muscle imbalance or ligament laxity (mechanical instability), or, conversely, decreased muscle flexibility and therefore decreased joint movement (Murphy et al., 2003a). It may also be the consequence of incorrect or inadequate rehabilitation (Kucera et al., 2005). Therefore, an emphasis on injury prevention, particularly to avoid re-injury, is of paramount importance.

2.5.4 Muscle activation and control – introduction

Injuries to knees (including to the ACL) and ankles may be related to the muscle activation (i.e muscle contraction) pattern at the time of injury. Considerable research has focused on muscle activation, or, more pertinently, inactivation, and the effect on injury risk (Hewett et al., 2005; Zazulak et al., 2007;, Benke et al., 2018). For example, Zebis et al. (2009) showed how the quantity of muscle activation effects ACL injury risk. It is important to understand all bodily segments and associated muscle activation relevant to injuries in hockey (a superior to inferior approach has been adopted).

2.5.5 Trunk motion and associated muscle activation

It has been suggested that trunk control is strongly associated with knee, ligament and ACL injury (Zazulak et al., 2007). A lack of control or 'trunk dominance' is defined by Hewett et al. (2010) as "the inability to precisely control the trunk in a three-dimensional space" (p.238). This lack of control leads to greater movement (flexion and lateral flexion or postural sway) and a decreased proprioceptive sensitivity of the trunk during landing.

The core of the body involves the active and passive structures of the trunk, specifically the lumbopelvic complex, which comprises: the lumbar vertebrae; the pelvis; the hip joints; and structures that make or restrain movement (Willson et al., 2005). This latter group includes the thoracolumbar spine, pelvis, gluteus maximus, trunk muscles and pelvic floor muscles (Borghuis et al., 2008). This is important because the core is where the muscles of the lower extremities attach (Akuthota & Nadler. 2004). Core stability is defined as: “The ability to control the position and motion of the trunk over the pelvis and leg, to allow optimum production, transfer and control of force and motion to the terminal segment in integrated kinetic chain activities” (Kibler et al., 2006, p.190). This can also alter kinematics (Kibler et al., 2006)

Core strength and function are important in all sporting actions as kinetic chains are involved in the transfer of force during movement. This transfer of force has been identified by Zazulak et al. (2007b) as a contributor to knee injury including ACL injury. The researchers found that lateral movement of the trunk could be used to predict significant ligament injury and that active repositioning error and a history of low-back pain among female players could be correlated with knee ligament injury with 91% sensitivity and 68% specificity. This relationship was not found in male athletes (Zazulak et al., 2007b). Furthermore, in a prospective biomechanical-epidemiological study that was conducted over three years, there was a difference in the deficit in proprioceptive repositioning in knee-injured female athletes (Zazulak et al., 2007a). Interestingly, with each degree of error, there was an increased odds ratio of 2.9 towards the occurrence of knee injuries. Active proprioceptive repositioning could be used to predict knee injury with 90% sensitivity (Zazulak et al., 2007).

The relationship between trunk control and knee injury may be due to hip and trunk muscle weakness, as this reduces the ability to stabilise the trunk, especially in the frontal and transverse planes (Leetun et al., 2004). These authors, along with Nadler et al. (2002), found that these weaknesses enabled greater leg hip adduction and internal rotation. Furthermore, Ireland (2002, as cited in Borghuis et al., 2008) and Zazulak et al. (2007) also reported that knee abduction and external rotation increased with hip and trunk muscle weakness and that this led to an increased risk of ACL and lower extremity injury.

The control of hip movement can be increased with simultaneous co-contraction of the flexion and extensor muscles (Arokoski et al., 2001). Leetun et al. (2004) indicated that core stability, hip and trunk strength played an important role in injury prevention, particularly in lower extremity injuries in women. Team-sport players inherently have to control their trunks during multi-directional movement (Borghuis et al., 2011). Soccer players are reported to show quicker reaction times of the core muscles (which include the erector spinae, rectus abdominus and external oblique) and increased postural control (impaired postural control is an indicator of low-back pain) than non-soccer players. This indicates that soccer players may have greater core neuromuscular control than non-players (Borghuis et al., 2011).

A number of studies (Anderson and Behm, 2005; Borghuis et al., 2011; Bronner et al., 2003; Ebenbichler et al., 2001) have reported that trunk and hip weaknesses (trunk instability) place the lower back at greater risk of injury and pain. Cissik (2011), in a systematic review of core exercises and performance, suggested that the role of the 'core' and the training of it required further research as the evidence was equivocal. Exercises that include the plank (including side plank), roll outs and those that extend the lumbar spine can help to develop core proprioception (Ekstrom et al., 2007). Other proximal muscles affect distal body parts during lower limb movement; for example, ankle injuries have been linked to a lack of gluteus maximus and medius activation (Hodges & Richardson, 1997).

Pelvic muscles such as the gluteals have been shown to affect the movement of the upper lower extremities in all three planes and hence to affect injury risk and performance (Willson et al., 2005). It has been suggested that in modern life, due to a sedentary lifestyle, gluteal activity has reduced, which has led to the development of 'gluteal amnesia' in some people (McGill, 2007). A deficit of activation of the gluteus maximus can cause instability of the pelvis (Willson et al., 2005), which has specific impacts on the sacroiliac joint (Arab et al., 2011) and on energy absorption during landing (Zazulak et al., 2005). Furthermore, impaired gluteal activation coupled with altered activation of hamstrings and erector spinae during hip extension can lead to a lower back injury (Reiman et al., 2012) and hamstring strains (Geraci & Brown, 2005).

Gluteal weakness and its effect on hip musculature have been shown to have several effects, in addition to the aforementioned lower back injury. These include greater hip adduction (Zazulak et al., 2005); internal rotation of the femur (Willson et al., 2005); a stiffening of the knee and lower leg (and therefore an increase in vertical ground reaction force (vGRF)) (Lephart et al., 2002) that may contribute to ACL sprains during landing tasks (Zeller et al., 2003); and ankle instability (Bullock-Saxton et al., 1994). There is some evidence of a difference in gluteal strength between genders. Zazulak et al. (2005) found that more females than males showed reduced activation of the gluteus maximus during single-leg landing. This muscle activation strategy is associated with increased quadriceps (rectus femoris) activity, which is strongly associated with ACL injury (Zazulak et al., 2005). These researchers also reported a 25% decrease in mean gluteus medius activation in female compared to male athletes (although not significant).

During locomotion, the gluteus medius controls movement in the frontal and transverse planes. Therefore, a reduction in activation can increase hip adduction and internal rotation (Semciw et al., 2013). There is some evidence that NCAA division one soccer females show significantly reduced gluteus medius activity during landing compared with their male counterparts (Hart et al., 2007), although these researchers did not find differences in the activity of any other lower extremity muscles. This may suggest there could be greater hip adduction, since the gluteus medius is a hip abductor, and reduced active energy absorption and a reliance on the passive structures. However, this small-scale study (8 per group) recognised that a much larger study to verify this finding was required.

Nakagawa et al. (2012) found that participants with patellofemoral pain syndrome showed greater hip adduction and hip internal rotation than non-sufferers, and that these hip effects were associated with reduced activation of the gluteus medius. Willson et al. (2006) reported a gender difference in hip abductor and external rotation (trunk and knee) strength, which could contribute to greater frontal plane projection angles. A further study (Willson & Davis, 2008) found similar results and reported that females were found to have greater knee abduction on landing than males. Khayambashi et al. (2015) also noted that impaired hip musculature strength was found to be a predictor of non-contact ACL injury in competitive athletes.

The evidence presented above suggests that controlling trunk motion via core stability and timely core muscle activation, can reduce knee, ligament and ACL injuries in all athletes, especially female athletes.

2.5.6 Knee motion and associated muscle activation

There has been considerable research into the mechanics of landing (e.g. Hewett et al., 2005; Lessi et al., 2017; Yu, Lin, & Garrett, 2006) and cutting (Bencke et al., 2013; McLean et al., 2004). Female sports players are four to six times more likely to sustain knee injuries than male players (Hewett et al., 2005). A large-scale (205 adolescent female team-sport players), prospective study indicated that the biomechanics of the ACL after injury were statistically significantly different compared with its biomechanics in the uninjured (Hewett et al., 2005). The differences were: a knee abduction angle that was 8.4° greater at initial contact and 7.6° greater at maximum, which caused greater knee abduction moments than in non-injured female athletes during landing. Maximum knee flexion was greater and peak vGRF was lower in the uninjured than in the injured group. Furthermore, knee abduction moment, angle and peak ground reaction force were statistically significantly correlated within the injured group. This strongly suggests that knee abduction throughout the movement could be a cause of ACL injuries as well as use of strategies to reduce the ground reaction forces (GRFs) through active force absorption. These landing characteristics informed the NMT programme and instructions that were used in this study.

Furthermore, the Hewett et al. (2005) study noted that injured athletes employed statistically significant less knee flexion (10.5°) compared with uninjured athletes during a jump-land task. The researchers later termed this ‘ligament dominance’ (Hewett et al., 2010). This landing strategy relies on the passive structures (ligaments and joints) rather than the muscles to attenuate forces. Hewett et al. (2005) also reported a statistically significant difference in vGRF, with the injured group having a 20% higher vGRF with hip adduction and knee abduction significantly correlated and a significantly shorter (16%) stance time compared with the uninjured. Decreased vGRF has been suggested to be related to strength and plyometric training. Lephart et al. (2005) undertook a study in which high-school female athletes (intervention group = 14, control group = 13) undertook a plyometric and balance intervention for seven weeks. Results from the study show a 7-8% reduction in vGRF in both groups during a jump-land task. The findings concurred with those reported by Hewett et al. (1996), who observed a 22% decrease in peak landing forces after plyometric training. Both studies indicate that hip and thigh musculature influence the vGRF and mechanics of landing (i.e. knee flexion).

Two studies (Hewett et al., 2005; Myer et al., 2006) noted statistically significantly greater (6.4 times more) knee abduction movement in the dominant leg in the injured group of players than that experienced by participants in the non-injured group. The studies highlight clear differences between those who were injured and those who were not. Other mechanics, pertinent to this thesis, that have been reported to contribute to knee injuries are: landing on the heels rather than the toes (Griffin et al., 2006) and foot pronation (Hewett et al., 2005) related to vGRF and knee abduction respectively.

Use of video evidence in elite handball showed that, typically, injured players (during a plant and cut, one-leg landing and deceleration) travelled at high speed with limited knee flexion (15° approx.) and knee abduction (15° approx.), and with all their weight on the injured side (Olsen et al., 2004). On average, however, there was neutral tibial rotation. Similarly, in elite basketball, coronal plane mechanics were a factor in ACL injuries. Significantly greater knee abduction was observed in injured females than injured males and showed a trend to be greater in injured females than in non-injured female controls (Hewett et al., 2009). Therefore, these studies concluded that females demonstrated coronal plane control strategies.

Hewett et al. (2010) also discussed landing strategies that involved quadriceps dominance and leg dominance. Leg dominance involves greater reliance on one leg than the other during tasks that are normally symmetrical. Quadriceps dominance refers to the preferential use of the quadriceps to stabilise the knee joint. This can lead to an increase in anterior shear stress and therefore may increase the strain on the ACL. This strategy has a greater prevalence in females, whereas males are hamstring dominant (Feldmann et al., 2010). This is partly attributed to greater pre-landing quadriceps activity (Bencke and Zebis, 2011; Zebis et al., 2016) and a greater quadriceps-to-hamstring ratio in females (Myer et al., 2009).

The prevalence of the landing strategy categories defined by Hewett et al. (2010) was quantified by Pappas et al. (2016). In a large-scale study (n = 721) into the biomechanical profiles of high-school female athletes during an unanticipated sidecut, 40% showed no biomechanical deficits during cutting and were deemed to be at ‘low risk’ of injury. A quarter (24%) of the cohort showed leg or quadriceps dominance, 22% showed trunk and leg dominance and 14% were ligament dominant. Therefore, 60% of all high-school girls were found to be at high risk of ACL injury (Pappas et al., 2016). Bencke et al. (2013), who studied female adult elite handball players, found some differences from the Pappas study between dominant and non-dominant legs; however, Benke et al. (2013) and Pappas et al. (2016) largely concurred.

Not all female athletes are at high risk of ACL injuries. Analysis of landing mechanics of elite dancers indicated that they experienced a much lower rate of ACL injury than athletes (Liederbach et al., 2008). This five-year prospective, large-scale study (of 183 female and 115 elite dancers) found that the ACL injury rate was 0.012 per 1000 exposures (with no significant differences between genders) compared with 0.27 - 0.31 (females) and 0.08 – 0.11 (males) per 1000 exposures (Agel et al., 2007) in basketball and soccer players. These findings are supported by a biomechanical analysis comparison between dancers and team-sport players of both genders (Orishimo et al., 2014). During a landing task, female team-sport players had significantly greater peak knee valgus compared with male players of team sports and all dancers. Female dancers also showed lower hip adduction torque than the other three groups. In addition, both male and female dancers demonstrated better trunk stability than team-sport players (Orishimo et al., 2014). The authors suggested that extensive landing training, including balance and jumping training for dancers, in some way accounted for these findings. The landing mechanics that contribute to knee injuries appear to be caused by particular muscle activation strategies, including the anterior/posterior and medial–lateral imbalances, in magnitude, ratio and timing between genders and in injured people compared with uninjured. These factors significantly impact injury rates (Myer et al., 2009).

This imbalance has been reported in both strength and activation. Females are reported to show significantly lower strength and activation of the hamstrings than the quadriceps (Ebben et al., 2010; Huston & Wojtys, 1996; Opar et al., 2012; Zazulak et al., 2005; Zebis et al., 2009). Opar et al. study (2012) found greater hamstring activation in males than in females. The lower levels of activation lead to reduced joint stability, increased anterior shear force and anterior tibial translation (ATT) and therefore increased risk of an ACL strain, especially at low knee flexion angles (Brown et al., 2014; Hughes and Watkins, 2006; Lloyd and Buchanan, 2001; Zeller et al., 2003). At very low flexion angles, the hamstrings may even contribute to ATT (Escamilla et al., 2012; Imran & O'Connor, 1998). Increased hamstring contraction encourages knee flexion and reduces the patella tendon tibial shaft angle. This process reduces potential strain on the ACL, particularly at knee flexion greater than 30° (Hughes and Watkins, 2006; Tsepis et al., 2004). In simulated model studies, hamstring strength has been shown to reduce ACL strain at low flexion (20°) angles (MacWilliams et al., 1999; Markolf et al., 2004). Similarly, Withrow et al. (2008) in a cadaveric study found that hamstring force could reduce ACL strain by up to 70% during the landing phase of a manoeuvre.

Myer et al. (2009) found, in a prospective study that involved high school and collegiate team-sport players, that those women who sustained an ACL injury had significantly lower hamstring strength than both male and female controls. Also, the injured women had similar quadriceps strength to the male controls, whereas the female controls had significantly lower quadriceps strength than the male controls. One of the functions of the quadriceps during landing is the absorption of impact, which has been shown to be lower in females compared with males. Reduced ability to absorb impact leads to the production of greater vGRF (Lephart et al., 2002). These results are consistent with computational models. Li et al. (2002) and Withrow et al. (2006) suggested that ACL loads increased as quadriceps force increased, all of which occur at low knee flexion angles (< 30°).

There is some evidence that maturation affects hamstring strength, and therefore hamstring/quadriceps ratio and potentially an injury. Ahmad et al. (2006) noted that men and women increased their hamstring and quadriceps strength with age. However, hamstring strength in females increased by 27% compared with 179% in males. In terms of quadriceps strength, in girls, this increased by 44% and in boys by 146%. Therefore, the hamstring/quadriceps ratio was found to increase from 1.73 in immature girls to

2.06 in mature girls, whereas it decreased from 1.58 in immature boys to 1.48 in mature boys (Ahmad et al., 2006). These changes affect the risk of anterior tibial translation and ACL injury and indicate the target population and potential content of an intervention.

Croce et al. (2004) and Russell et al. (2007) suggested that pre-pubescent males and females relied on the reactive response of hamstrings during landing, whereas post pubescents showed greater co-activation prior to the initial contact. There is some evidence that the experience level of the player affects hamstring activation. Sigward and Powers (2006) reported that experienced players showed a less protective strategy regarding hamstring activation than novice players. The authors suggested that novice athletes gradually polished their movements and gradually improved muscular efficiency, which reduced any ‘unnecessary’ muscle activation. However, Sigward and Powers (2006) acknowledged that further investigation was required into these phenomena.

Medial–lateral differences can lead to medial condyle lift (reduced medial joint compression), knee valgus and increased lateral knee joint compression, which increases the risk of an ACL strain (Myer et al., 2005; Zebis et al., 2008). These movements can be seen from the knee abduction and external shank rotation, which are common among females during landing (Ford et al., 2003). This may occur because of increased lateral quadriceps activation (Hanson et al., 2008; Myer et al., 2005).

In addition, there are significant differences between genders regarding medial–lateral hamstring activation (Besier et al., 2003). The action of the lateral hamstring (biceps femoris) can be up to four times greater than the medial hamstring function (semitendinosus) during landing in females (Rozzi et al., 1999). Similar findings have been reported during a side-cutting task (e.g. Zebis et al., 2009). Both contraction strategies risk compression of the lateral side of the knee, which opens the medial side and thereby increases the risk of a ligament strain (Guelich et al., 2016; Sell et al., 2004). Palmieri-Smith et al. (2009) found that both genders exhibited medial-lateral imbalances; however, the imbalance was greater in women. Females were also found to have reduced activation of vastus medialis and semitendinosus during a hopping task (Palmieri-Smith et al., 2009).

There is evidence that the timing of muscle contractions differs between genders; females exhibit earlier quadriceps activity during a task than males (Hanson et al., 2008; Huston and Wojtys, 1996; Zazulak et al., 2005). In contrast, females show signs of a slower hamstring response and a longer time to peak than males (Cowling & Steele, 2001; Huston and Wojtys, 1996). However, other studies have found no gender differences (Lewis et al., 2010). Therefore, the earlier and increased quadriceps activity compared with hamstring activity may be a fundamental factor ACL strain.

Following fatigue, muscle activation in both knee flexors and extensors is reduced (Kellis & Kouvelioti, 2009). This may result in greater reliance on either other muscle structures or the passive structures. However, the magnitude of the biceps femoris and semitendinosus activation has been found to be significantly reduced after fatigue in females, but not in males (Behrens et al., 2015). Also, the latency period for hamstrings appears to increase significantly following a fatigue protocol in females; it is significantly greater for both biceps femoris and semitendinosus – 7.4% and 6.4% increase respectively. In comparison, no significant change has been noted in males (Behrens et al., 2013; 2015). This latency period is likely to increase the risk of an ACL injury because of the significantly greater anterior tibial translation, as such injuries, often occur within the first 50ms of landing (Behrens et al., 2013; 2015).

Studies indicate that risks of injury are increased during side-cutting manoeuvres, especially during those that are unanticipated (within the first 50ms after landing) as these movements increase the load on the muscles. When sidestepping is unexpected, a 100% increase in varus/valgus and internal/external rotation is observed (Besier et al., 2003). Interestingly, there is no equivalent increase in muscle activation to counter this movement; however, a 10-20% increase in activation under unanticipated conditions has been reported (Besier et al., 2003). To address the imbalance, NMT has been shown to be effective in increasing the activity of hamstrings, and particularly semitendinosus (Zebis et al., 2016) which positively affects frontal plane knee motion (Hopper et al., 2017). Other research demonstrated that NMT increased medial gastrocnemius activity to reduce knee abduction (Fox et al., 2018). Furthermore, Hewett et al. (1996) undertook a co-activation study with female athletes with a strength and plyometric intervention in which the hamstring/quadriceps muscle peak torque ratio was increased, which significantly decreased knee ab/adduction moments and therefore reduced the ACL injury risk.

Hamstrings exhibit the highest injury rate of all lower extremity muscles (Petersen et al., 2011; Thorborg et al., 2011) including in team sports (Opar et al., 2012). Hamstring injuries are also prevalent in hockey (most number of injuries, 60% (approx.) of all injuries, in male hockey (Rees et al., 2020). Many hamstring injuries (specifically to biceps femoris) occur during fast running or eccentric contractions during actions such as high kicking (Askling et al., 2010). Of these injuries, most occur during or at the end of the swing phase or at the start of the stance phase as the muscles are lengthened and are subjected to high torques. Hamstring activation and strength have been shown to be important in the reduction of hamstring and knee injuries (Opar et al., 2012), as have reductions in hamstring/quadriceps ratio, medial-lateral imbalances, fatigue and age (Cameron et al., 2003; Dallinga et al., 2012; Opar et al., 2012). However, the causes of hamstring injury requires further investigation (Opar et al., 2012).

2.5.7 Ankle motion and associated muscle activation

There is limited evidence to explain the role and mechanism by which gastrocnemius, soleus and the other plantar flexors contribute to movement control during landing, compared with other muscle groups. The most common injury appears to be to the gastrocnemius and occurs at near full knee extension with dorsiflexion (Dixon, 2009; Harwin and Richardson, 2017) and in cases of previous injury (Green and Pizzari, 2017).

There is some evidence that gastrocnemius assists in ACL protection (Ali et al., 2014), particularly during large knee flexion (>40°). However, this evidence is inconclusive, particularly at low flexion levels (Adouni et al., 2016; Hashemi et al., 2011; Mokhtarzadeh et al., 2013). Morgan et al., (2014) showed through an actuated model study that the gastrocnemii forces that acted on the knee increased knee joint compression and decreased ACL strain. This study, therefore, showed that gastrocnemii with quadriceps increased knee joint stiffness and decreased knee and ACL injury risk. These studies seemed to agree on the effect of soleus on ACL strain and reported that this muscle was either an ACL agonist or had a negligible effect on ACL injury.

The role of each head of the gastrocnemius appears to be slightly different with respect to injuries. The lateral head has a role in the control of the knee, whereas the medial head is involved in the control of the ankle (DeMont and Lephart, 2004; Huston & Wojtys, 1996; Wolf et al., 1998). DeMont and Lephart (2004) found that pre-contact electromyography (EMG) activity of the lateral and medial gastrocnemius showed no gender differences in this muscle. However, Landry et al. (2009) found that females showed greater lateral and medial gastrocnemius activity pre-landing and early stance activity during an unanticipated sidecut, which they suggested may have placed the ACL under increased strain. Interestingly, Klyne et al. (2012) found that ACL-deficient participants in exercise activated their medial gastrocnemius for longer during a hop task than did a control group. This long activation period may be a strategy to maintain knee stability.

Conversely, ankle injuries are frequently reported in team sports. Instability of the ankles can be caused by several mechanisms, including decreased muscle activation (from hip to ankle musculature) and reduced proprioception. Steinberg et al. (2017), in a systematic review, investigated the relationship between hip-muscle performance (activation, strength and endurance) and ankle/foot injuries. They suggested a kinetic chain theory that supports that hip musculature performance is affected the incidence of ankle and foot injuries. Kinetic chain theory suggests that “a force applied to one of the segments produces motion at all other segments (kinetic chain) in a predictable fashion” (Karandikar and Vargas, 2011, p.740). EMG measurement has shown that lower extremity muscles on both sides of the knee (vastus lateralis, tibialis anterior, peroneus longus, tibialis posterior and soleus) affect ankle stability during the star excursion balance test (SEBT) (Change et al., 2011). Similar evidence has been provided by Van Deun et al. (2007), who found that the muscles of the whole lower limb, including gastrocnemius, contributed to the stability of the ankle.

Another study showed that instability of the ankle was linked to delayed peroneal reaction time when compared with functionally stable controls; however, no delay was noted in the processing of afferent input (Konradsen & Ravn, 1990). Other studies have reported increased soleus activity and decreased tibialis anterior activity during planned and unplanned activities (Wikstrom et al., 2010). These results suggest that players with chronic ankle instability (CAI) may have a deficit in neuromuscular control and are therefore at increased risk of injury. To limit the effects of CAI, balance and proprioception exercises are recommended (Robbins and Waked, 1998, McKeon et al., 2008 and Eils et al., 2010) including unipedal-based exercises for the greatest activation of ankle muscles (Borreani et al., 2014).

The role of the ankle and associated structures is important in terms of energy absorption. The ankle absorbs nearly 62% of the energy (in the sagittal plane) that is produced during a landing from 20cm (Saito et al., 2013) and nearly 90% in the frontal plane (Boo et al., 2018), depending, in part, on the landing strategy, which may be 'stiff' or 'soft'. The other structures and joints also play important roles. A 'soft' landing strategy reduces the magnitude of the energy that is absorbed by the passive structures (Norcross et al., 2013). Landing on toes first (compared with a heel strike) is part of a 'soft landing' strategy. This landing strategy also reduces the vGRF and the rate of force development. The magnitude of the vGRF has been strongly correlated with ACL injury risk (Griffin et al., 2006; Hewett et al., 2005; Orishimo et al., 2014).

2.5.8 Summary - risk factors

Several external factors predispose participants to injury. The type of sport and its nature influence the risk involved. There is equivocal evidence that skill level and the level of competition affect injury rates. Attempts to reduce the injury rate by modification of the rules of the sport and structure, particularly at youth level, appear to have some impact. For example, in hockey, more personal protective equipment has been introduced to decrease the number of contact injuries that are sustained during penalty corners. Initiatives that cover the structure and rules of the game and compliance with the rules have been implemented to reduce the numbers of injuries; however, these require continual monitoring and review.

There are several internal risk factors that can or cannot be modified to reduce injury. Of the non-modifiable risk factors that appear to affect injury risk, age and the occurrence of previous injuries seem to have some influence; however, the gender of players appears to have a significant influence. Females sustain injuries more frequently than males, especially post-puberty in the knee (Griffen et al., 2000; Griffen et al., 2006; Hewett et al., 2010; Prodromos et al., 2007; Zech et al., 2021)..

The motion of the trunk has a significant impact on injuries and especially on the ACL. Excessive flexion and lateral motion can be reduced through the performance of core muscle exercises within a NMT programme during landing and side-cutting.

There is similar compelling evidence regarding the antecedents of knee injuries. Deficits in hip and thigh musculature (especially of the gluteal and hamstring muscles) can lead other muscles, especially the quadriceps, to dominate and/or compensate for any deficits. The use of these muscles can exaggerate the knee motion and cause other structures (passive structure, especially ligaments) to restrain undesirable motion. Further to anterior–posterior differences, consideration is required regarding medial-lateral imbalances, especially in terms of magnitude and timing. The typical undesirable motions that are highlighted in the literature are hip adduction and internal rotation, knee abduction and external rotation and ATT. These movements can be limited, to some extent, by greater shank muscle activation (gastrocnemius, soleus and peroneals). Shank muscle activation and timing can improve knee and ankle joint stability, which may further impact the landing position and motion during landing as discussed in Hewett et al. (2005). Further factors that lead to injury include the landing strategy (stiff or soft) and, therefore, the vGRF that is created by the athlete during landing. However, subsequent reports argue that the role of the muscles of the shank, particularly the gastrocnemius, in ACL injury risk is unclear (Alentorn-Geli et al., 2015). Further research into the EMG, kinematics and kinetics in female hockey players understand risk factors.

2.6 Warm-ups

2.6.1 Introduction and definition

A warm up is undertaken before a sporting activity and can be defined as “techniques used to increase local muscle and core body temperature prior to vigorous exercise. Can be either active or passive and may be specific to the sport or exercise about to be performed” (Brooker, 2008, p.514). A period of 5 – 10mins of light-moderate cardiovascular and muscular endurance exercise is recommended (ACSM, 2017). This process is different to NMT, which is the development of neuromuscular control. Neuromuscular control is defined as “the unconscious activation of dynamic restraints occurring in preparation for and in response to joint motion and loading for the purpose of maintaining and restoring functional joint stability” (Riemann & Lephart, 2002, p.73). Further research into the EMG, kinematics and kinetics in female hockey players understand risk factors. Neuromuscular control interventions have been shown to significantly reduce all injuries (Soligard et al., 2008), specific injuries (73.4% reduction in noncontact ACL and 43.8% reduction in overall ACL injuries (Myer et al., 2013)). A review of ACL injury rates (Hewett and Myer, 2005; Hubscher et al., 2010; Emery et al., 2015), hamstring injuries (Petersen and Homlich, 2005; van der Horst et al. 2015) and ankle injuries (Hubscher et al., 2010) reported a significant reduction in injury rates following neuromuscular training.

A warm-up precedes most physical and sporting activities and is considered an important aspect of sporting performance (Bishop, 2003; McGowan et al., 2015) and may reduce the occurrence of muscle injuries (Woods et al., 2007). This section covers the physiological changes within the body that occur during different parts of a warm-up and the benefits that these changes have on both performance and injury prevention. A general warm-up prepares the cardiovascular, respiratory and neuromuscular systems through five to 10 minutes of movement such as cycling and running. A specific warm-up should involve those movements that will be used in the subsequent activity (Woods et al., 2007).

2.6.2 Benefits of warm-ups and their structure

There are many suggested benefits of a warm-up (Bishop, 2003; 2003b) and these can be classified as temperature or non-temperature related. The non-temperature benefits include increased muscular blood flow, elevated baseline oxygen consumption, post-activation potentiation and improved psychological preparation. The temperature-related benefits include decreased resistance of muscle and joints, the greater release of oxygen from haemoglobin and myoglobin, increased rates of metabolic reactions and nerve conduction, as well as increased ability to withstand thermoregulatory strain (Bishop, 2003; McArdle, Katch and Katch, 2015; Rathmacher et al., 2012). Output from the energy system is also increased (Febbraio, 2000), as is nerve conductivity, which is especially important for speed and power-based activities (Bishop, 2003; Ross & Leveritt, 2001).

Increased temperature has the disadvantage that it can lead to impairment of heat storage capacity and dehydration (Bishop, 2003). Additionally, the duration, intensity and timing of the warm-up must be tailored to the subsequent activity to avoid a decrease in performance (Bailey et al., 2009; Bishop et al., 2001; Bishop, 2003; Faigenbaum et al., 2005; Tillin & Bishop, 2009). The first element of the warm-up is performed to raise the temperature of the muscles by around 2°C (Saltin, 1968, cited in Bishop, 2003) without depletion of phosphate or glycogen stores. This is achieved within three to five minutes in a moderately intense warm-up and results in a rise in the maximum rate of oxygen consumption (VO_2 max) to approximately 60% of the heart-rate reserve (Dalleck & Kravitz, 2006). A total warm-up time of 5-10mins through the performance of a short, task-specific activity plus a short (up to 5 mins) recovery period (depending on the activity) has been reported to improve short-term performance (Woods et al., 2007). A rest period of five minutes is recommended at the end of a high-intensity warm-up to refill phosphocreatine stores (Bishop, 2003a).

In addition to the benefits of a warm up described above. There is an increased in muscle metabolism due to faster Adeosine Triposhate (ATP) turnover via increase in Creatine Phosphate (PCr) H+ accumulation, as well as increases in anaerobic glycolysis and muscle glycogenolysis (Gray et al, 2006; Gray et al., 2008).

Muscle fibre performance also changes. There has been an increase in the muscle cross-bridge cycling rate is one possible explanation for this higher reported turnover rate (Karatzafer et al., 2004). Muscle Fibre Conduction Velocity increases with neural transmission rate (Mohr et al., 2004). This may be due to the increase release of calcium from the sarcoplasmic reticulum during fibre membrane depolarization, membrane hyperpolarization as a result of increased Na+/+ pumping activity muscle fibre swelling and/or faster activation of muscle fibres are all plausible explanations for Muscle Fibre Conduction Velocity enhancement (Hoeven 1993; Hick et al. 1989; Gray et al., 2006). Further, temperature dependency is likely related to one of the underlying processes of muscle relaxation, such as calcium removal from the myoplasm, calcium dissociation from troponin and/or the cross-bridge detachment rate.

The speed of muscle relaxation can decrease at lower temperatures (22–25 C) (higher temperatures are 25-37 degrees C. Temperature dependency is likely related to one of the underlying processes of muscle relaxation, such as calcium removal from the myoplasm, calcium dissociation from troponin and/or the cross-bridge detachment rate (De Ruiter et al., 1999). Lastly, Mohr et al (2004) also positive changes in pulmonary and muscle oxygen uptake affected by temperature.

The structure of a warm-up that is used in intermittent endurance sports should be similar to one that is applied in individual sports (Cone, 2007). This researcher recommends that a warm-up should: start with an active stage that elevates muscle temperature and oxygen intake (VO_2); continue with progressive momentary exercises to improve static flexibility; move into dynamic flexibility exercises, such as squats; then prepare the neurons through the performance of movements that promote speed, agility and quickness (SAQ). Cone (2007) also recommends use of predictable movements, such as cutting, that are similar to those that will be used in the activity that follows, and it is recommended that the final set of warm-up exercises should include maximal speed exercises. These recommendations have yet to be empirically tested.

Jeffreys (2007) and Jeffreys (2018) suggest that the structure of a warm up could follow the RAMP principle. The ‘raise’ or pulse raiser section is an activity that raises the heart rate, increasing blood flow through active muscle, and raises body temperature. The ‘activation’ part of the warm up is to activate, perform exercises to contact or engage key muscle groups. In the ‘mobilisation’ section, the aim is to increase the range of motion with sports specific dynamic exercises. Finally, in the ‘potentiation’ section the aim to is to stress the body in preparation for the upcoming competition or session to induce post-activation potentiation – PAP - a phenomenon by which the force exerted by a muscle is increased due to its previous contraction (Robbins, 2005; Lorenz et al., 2011).

2.6.3 Effect of warm-ups on performance enhancement and injury prevention

In elite sport, the use of warm-ups is widespread, in contrast to recreational sports, where their use is less common (Bishop, 2003a; Fradkin et al., 2003). However, the benefits of a warm-up regarding injury prevention are not widely reported (Fradkin et al., 2006). In a systematic review, Fradkin et al. (2006) found that among the five included studies in the review, three reported that warm-ups reduced the incidence of injury, although two reported that warm-ups had no impact on injury incidence. It has been reported that specifically, a warm-up can reduce the incidence of muscle tears as it increases the elasticity of connective tissue and therefore the force that is required to tear the tissue (Altavilla et al., 2018; Safran et al., 1989). This is supported by figures that show that numbers of injuries spike after a break in play, such as half-time (Bixler and Jones, 1992). This may be attributable to the 1.5°C drop in muscle temperature that occurs between the end of the first half and the start of the second (Mohr et al., 2004). Fradkin et al. (2006) conclude that the weight of evidence supports the notion that warming up reduces injury rates.

There is strong evidence that performance is improved following a warm-up. Fradkin et al. (2010) reported that warm-ups improved performance across a variety of sports, tasks and components of fitness. This study reviewed 32 high-quality articles in which 79% of the studies reported an increase of up to 20% in performance after warm-up. Several factors could have influenced the results of the studies that did not report improved performance after a warm-up. Some involved: performance of warm-ups that had not been correlated with the sport (for example, jumping jacks before a throwing task); the imposition of a prolonged rest period after the warm-up but before the performance; and/or the involvement of children. However, the optimal structure of the warm-up for different sports is far from clear and therefore requires further investigation (Fradkin et al., 2010). The participants initial training status or conditioning levels may impact of the results of the study as the absolute intensity for an untrained person is different from a trained person (Fradkin, 2010). The impact on aerobic activities is limited; some studies report only a small increase in performance (Gray & Nimmo, 2001; Wittekind & Beneke, 2009).

Similarly, there is a strong association between the performance of a dynamic warm-up and improved performance in terms of power, strength and agility, when compared with the performance of a passive warm-up or no warm-up; 42 vs 41cm during a CMJ (Curry et al., 2009); 9.77s vs 9.7s for a T-drill (McMillian et al., 2006). Also, in performance data from Silva et al. (2018) and Yuktasir & Kaya (2009). In team sports, Pagaduan et al. (2012) reported that the carrying out of progressive exercises that mimicked the activity, without causing fatigue, produced better performance than both no warm up and passive static stretching. Similarly, Faigenbaum et al. (2005), in a study that included children comparing warm up protocols, found significantly superior performance in a vertical jump, long jump and shittle run following a dynamic warm up versus a static. Saez-Saez de Villarreal et al. (2007), who investigated explosive movements with volleyball players, reported significantly greater countermovement jump performance following an active warm up compared with the pre-warm up test and no change in the control tests. In addition, 20m sprints and countermovement jumps significantly improved among elite netball players following a 15-minute dynamic warm up compared with 15 minutes of static stretching (Taylor et al., 2009).

2.6.4 Stretching, injury prevention and performance

Cone (2007) recommends a period of pre-performance stretching following a pulse raiser. This is subsequently followed by dynamic flexibility and speed, agility and quickness exercises. However, there is an ongoing debate as to which type of stretching is optimal (Small et al., 2008). The choice of stretches appears to be related to the type of activity to be performed (Safran et al., 1989; Witvrouw et al., 2004) and the timing of the planned activity. McHugh et al. (1999) reported that greater flexibility can limit exercise-induced muscle damage and with greater intensity and duration. This study also suggested that, in this case, static stretches increased flexibility and reduced levels of injury. Stretching appears to increase hamstring flexibility significantly (Woods et al., 2007). However, these authors concluded that the total results were equivocal. Static stretching appears to benefit activities that involve movements with a large range of motion (McHugh & Cosgrave, 2010).

The effect of stretching varies with the type of activity. Kubo et al. (2002) reported that resistance training significantly increased the stiffness of tendons and stretching reduced the stiffness (i.e. increase compliance and therefore joint movement) but not significantly. Static stretching did increase the compliance and, in theory, reduced the risk of injury, as the stretched tendon did not reach the maximal energy-absorbing capacity (Kubo et al., 2002). However, it has been suggested that stretching before or after exercise does not reduce the risk of injury (Herbert & Gabriel, 2002; Shellock & Prentice, 1985; Shrier, 1999).

In terms of the effects of static stretching on performance, it has been suggested that static stretching increases tendon compliance and negatively affects the use of elastic energy which, in turn, affects the performance of actions that involve a stretch-shortening cycle (explosive actions) (Kubo et al., 2002; McMillian et al., 2006). The latter reported significant better T-shuttle, medicine ball throw and 5-step jump. Furthermore, activities that do not involve stretch-shortening movements or involve a few of them, such as jogging and swimming, do not benefit from static stretching as it reduces muscle efficiency (Wilson et al., 2010). In addition, a warm-up with static stretches does not appear to have a negative impact on sprint performance however, dynamic stretching was a more effective preparation for high-speed performance (Little and Williams, 2006; Stewart et al., 2007). On the other hand, Taylor et al. (2009) and Bishop and Middleton (2013) suggest that there is no significant impact on the performance of sprint and agility tasks following static stretching if succeeded by high-intensity activity-specific exercises. However, there was significantly reduced sprint and vertical jump performance if only static stretches are performed (Taylor et al., 2009). Similarly, static stretching reduces the performance of muscular-strength tasks if the static stretches last for more than 30 seconds (McHugh & Cosgrave, 2010). Furthermore, static stretches that last for more than 60 seconds appear to affect negatively all types of sporting movements as static stretching increases the range and motion and decreases the musculotendinous stiffness (Kay & Blazevich, 2012).

Abernethy and Bleakley (2007) and Lauersen et al. (2014) conducted systematic reviews of randomised controlled trials (RCTs) that considered injury prevention strategies and reported that stretching was not effective as an intervention measure to reduce the incidence of injuries. Small and Naughton (2008) also in a systematic review of RCT's largely agreed as they concluded that static stretching was not effective in reducing injury risk. However, they found some support for static stretching as a strategy to reduce the incidence of musculotendinous injuries. The debate will continue until more high-quality, randomised, clinically controlled studies are completed (Small et al., 2008).

2.6.5 Dynamic warm ups

Dynamic stretching is suggested to be beneficial across fitness components, especially in those body parts that are used in hockey. McMillian et al. (2006) showed, with male youth team sport players, that performances of power-based exercises were improved after a dynamic warm-up compared with the performance of a static or no warm-up. In addition, when different types of stretching were compared, it was found that team-sport players completed speed and agility-based tasks significantly quicker after a warm-up that involved a dynamic-stretch protocol than after warm-ups that included either static stretches or no stretches (Alikhajeh et al., 2012; Little & Williams, 2006). Similarly, Herman and Smith (2008) showed that over a four-week period, wrestlers (n = 11) who performed a dynamic warm-up showed enhanced muscular endurance, strength, agility and anaerobic capacity, while there was no difference between the before and after results in the static-stretching group (n = 13). Dynamic stretching can even reverse the negative effects of static stretching (Bishop & Middleton, 2013). Conversely, Curry et al. (2009) found no significant differences between performance outcomes according to the warm up procedure. Although not statistically different, the trend for counter-movement jump performance increased after performing both light aerobic activity and dynamic stretching whereas after static stretching the performance decreased from the pre-test. From the results presented here, there appears to be enough evidence to suggest that dynamic stretching improves performance. The improvements are often seen in strength, power and agility movements, i.e. movements and components of fitness that are prevalent in hockey.

2.6.6 Warm-ups in practice

There is a dearth of research available regarding the implementation of warm-ups in practice. A study of golfers found that only 54% of them performed any kind of warm-up before they played, while just 3% performed an ‘adequate’ warm-up; most just performed practice swings on the tee (Fradkin et al., 2001). A subsequent study reported that few golfers warmed up (70% stated they never or seldom warmed up) while only 3.8% always performed a warm up (Fradkin et al., 2003).

In a team-sport context, Steele (1990) reported that only 47.5% of veteran players performed warm-ups which the author attributed to a previous injury. McManus et al., (2006), in a more recent study of 368 recreational netball players, 60% did not perform warm-ups and this was suggested to increase injury risk by 48%. In contrast, in football, the average duration of the warm-up in the professional game is around 31 mins with a wide range (15 – 45 minutes) (Towlson et al., 2013). These warm-ups are followed by a recovery period of 12.4 mins before the start of the match (Towlson et al., 2013). Interestingly, injury prevention is not amongst the important elements of warm-ups that are reported by professionals (Towlson et al., 2013).

Avest (2010) investigated the use of warm-ups in hockey, as well as the differences between theory (as defined by each coach) and practice. This study used an observational approach to assess the content of warm ups with a follow-up coach interview. The results of the 13-team observational study (8 men's, 5 women's teams) suggested that warm-ups that were employed in semi-elite hockey lasted for 35.66mins, with a 2.66min pulse raise, 12min of activation and mobilisation and 21min of potentiation. Avest (2010) also investigated the amount of time that coaches would like to spend on warm-ups and found that coaches would have liked to warm up for a longer period (mean = ~38 minutes). However, the comparison to the evidence-based recommendations is an area for further investigation. Avest (2010) also observed that 77% of the warm-ups consisted of static stretching and that all the warm-up routines contained dynamic stretches. However, the occurrence of neuromuscular training was not reported. This study used a convenience sample (both level and geographically) therefore further investigation is required.

2.6.7 Summary – warm-ups

It is suggested that warm-up procedures may have both performance and injury prevention benefits primarily through the increase of muscle temperature and that these benefits can be achieved by following the raise, activate and mobilise and potentiate format. In the mobilise section, some athletes perform static stretches;

however, the evidence suggests that the benefit of their inclusion is limited from both injury prevention (increases compliance and decreases joint stability) and performance perspectives. Conversely, the inclusion of dynamic and sport-specific movements has more empirical support. The additional benefit of the inclusion of NMT will be discussed in the next section.

In contrast, the inclusion of static stretching appears to little impact on injury rates and also appears not to improve performance. Therefore, there is no evidence to support for including static stretching in a future intervention.

The performance of warm-ups in some sports seems to be limited. However, in sub-elite hockey teams, the performance of warm-ups is frequent and they contain the recommended stages, but there is a high prevalence of static stretching. The evidence for this, however, comes from a single study. This study also investigated the coaches' attitude and discovered that they would like to spend more time on the warm-up process. This attitude is not universal, and some coaches do not list injury prevention as an outcome of a warm-up. The attitude of the coach influences an athlete's behaviour. However, as there is a dearth of evidence, further investigation is required and this would be the research topic in chapter 4 of this thesis.

2.7 Neuromuscular training

2.7.1 Introduction

The previous sections focused on the benefits of warming up before participation in sport. However, Gambetta (2007) suggests that the stimulation of the nervous system is the most important part of the warm-up. It is acknowledged that a "one-size-fits-all" approach is not appropriate (van Beijsterveldt et al., 2013, p.263). This section discusses the principles behind NMT and assesses its effect on injury prevention and performance enhancement. This section also provides implementation, dosage and delivery suggestions for NMT programmes.

2.7.2 Neuromuscular control

When the body intends to move, the internal receptors of the tendons, joints and muscles (predominantly golgi tendon organs, muscle spindles and articular receptors) send neural signals to the central nervous system (CNS). These signals influence the response and therefore the movement (Sherrington, 1906, cited in Lephart and Fu, 2000). This process involves the information processes of other sensorimotor systems for visual, somatosensory and vestibular input (Lephart and Fu, 2000). The sensorimotor system provides information for the CNS, either through the basal ganglia, cerebellum or reflex arc depending on the sensory information, which, in turn, elicits a motor response from the motor-control centres. This response could be from the brain stem, cerebellum or the spinal or cerebral cortex, depending on the speed and automaticity of movement and movement requirements (Biedert, 2000; Riemann and Lephart, 2002). The spinal cord, as well as being a conduction pathway, can elicit some movement due to reflexes that are based on sensory information (Riemann and Lephart, 2002). These reflexes have short response times and produce basic movements that contribute to joint stabilisation. The function of the brain stem is to coordinate skeletal muscle and motor patterns for more complex tasks, which pass through this structure.

In the context of neuromuscular control, the brain stem is important for postural stability and to control movement, since it contains the vestibular nuclei and apparatus. The cerebellum is important in the planning and control of fast, complex tasks. It is also involved in the sensory feedback mechanism, which times and evaluates the completed task so that corrections can be made. The basal ganglia, in a similar way to the cerebellum, assist with complex motor patterns that are passed from the cerebral cortex. They also control complex motor patterns and trigger cyclical actions such as running. Additionally, the basal ganglia are involved in the maintenance of posture and muscle tone (Biedert, 2000).

The cerebral cortex controls the most complex voluntary movements, whereas the primary motor cortex processes sensory information and directs initial activation of the muscles (including force and direction). The pre-motor area organises and prepares the motor commands and works with the supplemental motor area, which principally programs complex motor patterns and those that involve groups of muscles (Riemann and Lephart, 2002b).

2.7.3 Goals of neuromuscular training

NMT is performed with the aim of “enhancing the unconscious motor response through the stimulation of both afferent signals and central mechanisms that are responsible for dynamic joint control” (Risberg et al., 2001, p.620). The purpose of the training is to provide scenarios that elicit afferent signals that stimulate an efferent motor response. Additionally, the process maintains or restores muscle activation to promote stability. These activities are potentially injurious and therefore must be recreated each time they are required. In a controlled and progressive environment, neuromuscular adaptations occur and, therefore, neuromuscular control can be re-established and the joint can be protected from (re)injury. This process can be achieved through the development of proprioceptive and kinaesthetic sensation, dynamic joint stabilisation, reactive neuromuscular control and functional motor patterns (Lephart et al., 1996). These elements promote and develop afferent pathways (greater sensitivity), muscle stiffness (less compliant, therefore greater joint stability), agonist/antagonist co-activation (increases joint stability), reflex muscle activation (a quicker response to forces e.g. vGRF) and onset and magnitude of muscle activation (adopting a muscle-dominant landing strategy and greater performance) (Swanik et al., 1997). To develop the required neuromuscular system response, several studies have different approaches.

2.7.4 Elements of NMT and rationale

To develop proprioception and kinaesthesia, the articular receptors and mechanoreceptors, including the muscle spindles and golgi tendons, must be stimulated. The inherent computation of the joint position and subsequent modifications of muscle activation to maintain the desired joint position is often referred to as neuromuscular control (Jonsson et al., 1989) and balance (Swanik et al., 1997). This control requires the transformation of afferent signals into an efferent response, as feedback or feed-forward. This transformation can be achieved by loading the axial system via the performance of closed-chain exercises or through continuous participation in sport, which can promote greater awareness in the athlete of joint motion through the provision of feed-forward and feedback. Evidence of this awareness has been demonstrated in work with highly conditioned athletes, who were pitted against sedentary controls in situations in which gymnasts could detect passive movement, in a knee flexion task, significantly more accurately than the untrained controls (1.1° +/- 0.18 vs. 1.9° +/- 0.21°, P = 0.011) (Lephart et al., 1996).

To promote preparatory and reactive muscle stiffness, exercises that involve eccentric loading can positively alter muscle tone and stiffness. These exercises lead to the proliferation of connective tissue and increase muscle-spindle activity (LaStayo et al., 2003). Lower-extremity muscle stiffness can be achieved through the performance of closed-chain activities that contain significant phases of eccentric muscle contractions, such as backward stepping and downhill locomotion (LaStayo et al., 2003). Also, actions that include stretch-shortening cycles such as plyometrics, particularly those that place an emphasis on the landing phase, provide eccentric loading to the hamstrings (Davies et al., 2015). This promotes the tendinomuscular receptors, which then provide information on joint activity and motion while they develop or establish reflex pathways, the muscle spindle system, and the cortical motor control centres. The development of muscle stiffness can be promoted via the performance of repeated low-load and high-repetition activities in muscles that twitch slowly, such as those involved in postural control (Swanik et al., 1997). These results can be achieved through strength- and power-based training. Power-trained athletes have been shown to have greater muscle stiffness than endurance-trained athletes, as power-trained athletes enjoy faster and greater onset of pre-activation, prior to joint loading than their endurance-trained colleagues (Swanik et al., 1997). This population's neuromuscular system may react quicker to landing forces therefore less reliance on passive joint structures and reducing the possibility of injury.

Increased muscle spindle activity also increases sensitivity and shortens reflex times. Perturbation training has been shown to develop a reduction in reflex times, for example, through the performance of exercises on unstable surfaces (Linford et al., 2006). Enhancement of the reflex pathway between joint loading and muscle activation increases dynamic stability. The purpose of the development of proprioception and kinaesthetic awareness is to develop or re-establish neurosensory characteristics of ligaments and increase the sensitivity of 'secondary peripheral afferent signals'. This increased sensitivity has been shown to normalise joint motion and position sense (Lephart et al., 1997). This is to say, detection of any movement of a body segment and it's direction is greater. Therefore, potentially any error detection can be responded to more quickly and with greater accuracy.

This can be achieved through progressive balance training, repositioning of joints during movement with verbal feedback, closed-chain balance exercises and stiff leg deadlifts and lunges (Myer et al., 2008).

To stimulate articular receptors, joint compression is required and can be achieved through closed-chain activities. Additionally, conscious repositioning of joints leads to increased proprioception and kinaesthesia. In time, and with repetitions, this joint control becomes unconscious.

Joint stability can also be achieved through agonist and antagonist co-activation to balance the forces that are exerted on a joint (Latash et al, 2018; Piscitelli et al., 2017). This reduces the loads that are placed on passive structures such as articulated joints and ligaments. Development of anticipation, or pre-activation and reduction of the time that is taken to react to joint loading, increases dynamic stabilisation. Swanik et al. (1997) have proposed that placement of the joint in a vulnerable position may be required in order to develop this element of the neuromuscular system. However, under controlled conditions, modes of training such as balance training on stable and unstable surfaces can be implemented. Additionally, more dynamic balance training via a slide board can be used to develop co-activation (Dedinsky et al., 2017). Closed-chain exercises can develop co-activation (e.g. hamstring and quadriceps), preparatory muscle stiffness and reactive qualities, especially if they entail a large eccentric component, such as single-leg squats (Begalle et al., 2012), the Nordic hamstring exercise (Opar et al., 2014), and plyometric exercises that include split squat jumps, multi-plane hopping and box jumps (Chimera et al., 2004). These types of exercises develop the efferent pathways and the neuromuscular system in response to stretch/shortening cycles and concentric and eccentric contractile exercises. All of these are important to provide stimuli to enhance the response speed and magnitude that encourages the early onset of muscle activation and reflex pathways (Linford et al., 2006).

Reactive neuromuscular control, which refers to the pathways between the receptors and the muscles, can also be developed through unanticipated scenarios and with some disturbance, for example, landing after an unexpected perturbation. Training can reduce the reflex response time and develop responses in these situations (Linford et al., 2006). Swanik et al. (1997) stress the importance of this element to promote muscle activation from reflexes to develop stable joints. Perturbation training can be implemented by balance training that may involve, for instance, alteration of the centre of mass or of the line of force from the joint centre via contact, catching a ball from a toss or locomotion on a soft and slightly moveable surface. More advanced, intense training in this mode could involve, for example, hopping on a trampoline, and multi-directional or multi-planar hopping. These exercises could be done in isolation or as part of a combined programme.

The final aspect of this type of training is the development of functional activities (movements that occur in everyday life). Development of specific motor programmes stimulates the afferent signals, muscle co-activation, reflexes, balance and pre-programmed motor control (Swanik et al., 1997). More recently, Myer et al. (2008) recommended sport-specific manoeuvres from conscious to unconscious control; for example, side-stepping in an anticipated move followed by an unexpected move. This may place body structures in positions that are vulnerable to injury; however, this can be done in a progressive and controlled manner. In the lower extremity, this mode of training can be developed with exercises that include backward walking/running, cross-over step locomotion, acceleration and deceleration, side-steps and pivot movement patterns. Once an athlete can complete these movements successfully and with confidence, sport and position-specific movements can be added. These manoeuvres can develop the aforementioned aspects of neuromuscular control with more specificity. Example exercises include shuttle runs, sprinting (both forwards and backwards) and moving and collecting an object.

2.7.5 Summary – Neuromuscular training

Tasks that improve feedback (and subsequently feed-forward) from the articular and tendinomuscular mechanoreceptors to the cerebral cortex and brain stem of the CNS and that elicit a subsequent response via efferent pathways and muscle activation are important to enhance motor control. This helps to maintain muscle stiffness, functional joint stability and neuromuscular control. NMT involves the performance of these tasks to develop or to re-establish proprioception, kinaesthesia, dynamic joint stability, reactive neuromuscular control and functional motor patterns. Participation in balance training, reflex facilitation via reflex training and stretch-shortening activities is important to develop neuromuscular control and functional stability. To develop muscle stiffness (and therefore dynamic joint restraint), eccentric loading (for example, the Nordic hamstring exercise) and stretch/shortening exercises (for example explosive, sport-specific movements) are recommended. In addition, the reflex responses can be improved by the use of unstable platforms and perturbation training. For all elements of NMT, transfer from a conscious to an unconscious scenario with ever-increased reaction times is recommended, as this can elicit greater fidelity between training and sporting scenarios. These recommendations were adopted in the development of the intervention that was used in the work described in chapter 5 of this thesis to facilitate the adaptations that are outlined in this section.

2.7.6 NMT and injury prevention

This section examines the effect on injury rates that is caused by the application of each of the methods of NMT that have been described in the sections above. This information has been used to inform the NMT programme that was undertaken in study three.

In a systematic review that contained high-quality RCT studies (n=68) and a subsequent meta-analysis (n=60), the odds ratio for the reduction of injury through the use of exercise-based interventions overall was 0.55 (95% CI; range 0.46-0.66) (Leppänen et al., 2014). Other interventions included the insertion of insoles (OR 0.51; 95% CI; range 0.3-0.81), the application of external supports to joints (OR 0.39; 95% CI, 0.31-0.49), the use of personal protective equipment (OR 1.06; 95% CI, 0.91-1.24) and stretching (OR 0.92; 95% CI, 0.8-1.06) (Leppanen et al., 2014). Therefore, of all the interventions that were reviewed, exercise-based interventions were found to be the most effective (Leppanen et al., 2014).

The exercise-based interventions appeared to be effective; however, not all elicited the same injury-reduction effect. The strength-based programmes offered the greatest protective effect, followed by balance training, multi-intervention with balance-board training, and other multi-intervention strategies. Interestingly, warm-up programmes were found to be the least protective against injury (Leppanen et al., 2014). Stretching was shown not to offer protection (OR 0.92; 95% CI, 0.8-1.06); nor did the wearing of modified shoes or interventions that involved the viewing of preventative videos (Leppanen et al., 2014).

A multi-component strategy to reduce injury rates is recommended by Brunner et al. (2019). This study evaluated high-quality systematic reviews and showed that the most effective combinations for reducing lower extremity injuries included strength, proximal control, agility, plyometric, balance and technique exercises (Brunner et al., 2019)

Several studies that were reviewed in the Brunner study (Lauersen et al., 2014; Sugimoto et al., 2014; Sugimoto et al., 2015; Sugimoto et al., 2016) described the exercises that had been employed for each element of NMT. Each NMT programme was constructed differently and there was variation in the choice of exercises and the repetition numbers, which were set according to the outcome measure. Despite this variation, common themes emerged. Effective programmes included a balance section in the form of postural exercises with an unstable support base; for example, a one-legged balance on a soft mat or wobble board (Myklebust et al., 2003). However, balance exercises alone appear not to be effective (Söderman et al., 2000). A strength section is required to promote the generation of force development, for example, squat or Nordic hamstrings (Pasanen et al., 2008). A plyometrics section is necessary to develop the stretch-shortening cycle, for example, jumping and landing (Donnelly et al., 2012). Also, exercises in core stability, which are also referred to as proximal control exercises, such as a plank or side plant, are recommended for inclusion in a NMT programme (Waldén et al., 2012).

Several other factors have been reported to affect the effectiveness of NMT programmes. There may be an inverse dose-response relationship (i.e the greater the quantity of training, the lower the injury rate); performance of NMT for at least 30 mins, twice per week, produces a meaningful clinical effect (Fort-Vanmeerhaeghe et al., 2016; Sugimoto et al., 2014). Furthermore, the programmes with high compliance rates (66%

+) report greater injury reduction effectiveness (an incidence rate ratio of 0.18) whereas studies that reported low compliance (<33%) found a much-reduced effect (an injury incidence rate ratio of 0.88) (Sugimoto et al., 2012). NMT programmes are effective for both male and female athletes (Alentorn-Geli et al., 2009) but the reduction of ACL injuries has been reported to be greater in females (Prodromes et al., 2007). The optimal age at which the effect is greatest appears to be the mid-teens group (Sugimoto et al., 2016). Lastly, the implementation of preventative NMT with feedback, especially with an external focus, enhances effectiveness (Benjaminse et al., 2015). The feedback could be provided by a coach or health professional to improve compliance (Sugimoto et al., 2015).

There are factors to consider other than the content of a NMT programme. These range from the gender of the athletes who undergo the programme to their ages, levels of compliance, dosage and the delivery mechanism. Substantial reductions in injury rates can be achieved with high compliance rates and sessions that involve feedback and are conducted frequently (dosage) (20-25 minutes each) among late teenage female participants. The evidence that is provided in this section influenced the structure and content of NMT that was applied in chapter 5 of this thesis.

2.8 Sport-specific team-sport warm-ups

2.8.1 Introduction

There are several sports in which organisers recognise that injury rates can be reduced with the implementation of sport-specific warm-ups. Sports that range from football to floorball, Gaelic football to netball and handball to hockey could potentially benefit.

2.8.2 Examples of sport-specific warm-ups

Floorball, which has been described as “hockey played indoors” (Pasanen et al., 2008, p.1), has an injury rate of between 40 and 50 per 1000 games hours and this rate is considered high (Pasanen et al., 2008). In response, a NMT programme to reduce the incidence of knee and ankle injuries through the performance of running, balance and control exercises, plyometrics, leg strengthening and lower-back stretching was developed (Pasanen et al., 2008). This large-scale (n = 457), cluster RCT study on the effects of floorball on injury rates that involved elite and sub-elite female participants (mean = 24 years) was conducted. The researchers reported a high level of compliance and a significant reduction in the number of lower extremity (66%) and non-contact injuries (incidence rate ratio (IRR) 0.7 overall, 0.34 for non-contact injuries) over a six-month period.

The most widely investigated and referenced NMT programme is known as 'FIFA 11+'. The programme involves running, strength awareness and neuromuscular control exercises that are performed alongside static and dynamic movements. A large-scale (1055 players in the intervention group, 837 in control), cluster RCT was conducted to test the effects of a comprehensive warm up programme on youth female players (mean age 15.4 years). After the performance of the recommended minimum of two training sessions per week for eight months, the number of injuries in the intervention group was reduced rate ratio (RR) of 0.71. There were significant reductions in the numbers of severe and overuse injuries (Soligard et al., 2008). The coaches that implemented the programme received training and supporting materials that included advice on movement technique that could be used to provide feedback. Many studies have investigated this intervention. A recent systematic review and meta-analysis that considered only cluster-RCTs, showed that use of the FIFA 11+ programme significantly reduced overall injury rates (IRR = 0.75, p=0.04) and use of the FIFA 11+ programme also significantly reduced overall injury risk (IRR = 0.61, p < 0.001) (Thorborg et al., 2017).

The Gaelic Athletic Association (GAA) has published the GAA 15-injury prevention programme/warm-up (GAA Learning, n.d.) which consists of an eight-week running-based series of exercises that include core and lower extremity strengthening, followed by balance and plyometrics exercises. The programme was evaluated through the performance of a randomised cluster trial among young adults (18 – 19 years, n = 41) and injury rates in the intervention group were significantly lower than those of the controls, with moderate effect size and superior Y-balance test and landing error scoring system (LESS) scores in the intervention group compared with controls (O'Malley et al., 2017).

Several programmes have been developed to reduce injury rates in handball (Holm et al., 2004; Myklebust et al., 2003; Petersen et al., 2005; Zebis et al., 2008). Myklebust et al. (2003) conducted a large-scale prospective study to explore the effects of an ACL injury prevention programme over three seasons among elite and sub-elite female handball players. The results showed that there was a greater effect in the second season (OR year 1 = 0.87, OR year 2 = 0.64). The authors noted a large difference in injury risk for the elite players (OR = 0.06) between the intervention and control groups. The result may be due to the greater compliance of the elite players compared with the sub-elite (all divisions = Year 1 - 26%, Year 2 – 29%, elite division players – year 1 = 42%, year 2 = 50%).

Two other large-scale prospective studies with similar interventions investigated the effect of NMT programmes on the numbers of knee and ankle injuries among handball players. They reported reductions in injury rates in the intervention groups at ORs of 0.53 (Olsen et al., 2005) and 0.17 (Petersen et al., 2005). One of the possible reasons for these reductions in injury rates could be because semitendinosus activity was increased (23%, $p<0.0001$) and vastus lateralis activity was decreased (23%, $p<0.0008$) prior to landing in another RCT, which involved adolescent (15 – 16 years) female handball and soccer players (Zebis et al., 2016). The changes in semitendinosus activity could decrease both anterior tibial translation and knee abduction.

In netball, NetballSmart in New Zealand (New Zealand Netball, n.d.) applied an exercise programme that included strengthening of the core, hamstrings, balance, dynamic stretching, multi-directional running, landing plus landing after contact and sidestepping. A study of the effectiveness of NetballSmart by Kearney (2019), with junior female club players (10 – 19 years) over 18 months, reported an 11% reduction in injury rates and a particular reduction of 6% in ACL injury rates following an 18-month intervention period. There was a greater reduction in the 15 – 19-year-old group compared with the 10 – 14 year-olds. There were few details reported on the implementation of the programme, such as compliance, therefore further investigation is required.

Also, in netball, Hopper et al. (2017) conducted an RCT to investigate the effects of a six-week NMT programme on 11-13-year-old female club netball players. They reported an increase in bilateral knee marker distance at maximum knee flexion during a bi-lateral landing task. Also, during a unilateral landing task, knee internal rotation was significantly reduced at the same time point. In both tasks, significant decreases in vGRF were observed with no significant pre/post changes in the control group. Furthermore, an increase in performance (vertical jump height, 505 agility, 10 and 20m time) was noted in the intervention group against no increase in the control group.

In hockey, Weir et al. (2019) undertook a study that involved an eight-week ACL injury reduction intervention with elite, female hockey players (n = 26, mean age 22.1 years) following a control season. The programme focussed on increasing knee flexion at foot strike, trunk control, strengthening of hip external rotators and increasing the strength of the gastrocnemius muscle through the use of plyometrics, balance and resistance-based exercises. The study reported injury rates, EMG, kinematics, kinetics and performance over a 25-week period (nine weeks of intensive training - 4 x 20mins per week - followed by 16 weeks of maintenance – 3 x 10min per week) that followed a control season. The maintenance training (3 x 10min per week) continued in the second intervention season. Study findings showed a reduction (non-significant difference) in overall injury rates for the lower body (control season = 23/1000 players hours to 15.7 in intervention season 1 and 5.5 in intervention season 2). Also, there was a reduction in the ACL injury rate from 0.4/1000 hours in the control season to 0.0 during the intervention period. However, there was a small increase in the knee injury rate in the first intervention season (from 2.1/1000 hours in the control season to 2.9 during the first intervention season) but reduced to below control season in the second intervention season. The study also noted a very low ACL injury rate during the control season. Weir et al. expected to report more lower extremity, knee and ACL injuries during this period. The total gluteal muscle activation was increased by 30% during weight acceptance of an unplanned sidestep manoeuvre with no other statistically significant EMG results. The ‘responder’ athletes (defined as an athlete with a pre-post difference (reduction) with a moderate to large effect size (d > 0.5) in peak knee valgus moments), also termed ‘high-risk’, showed significantly reduced peak valgus activity. The performance measures showed that the bench press, bench pull strength and 10m split of 40m speed were significantly increased in the first intervention period, but in the second intervention period, the figures returned to the level that had been seen in the control season. Taken together, the figures indicated a net 6% increase in the multi-stage fitness test (aerobic capacity) from the control period to the end of the second intervention. The results of the study indicate that a NMT programme can potentially show effective results with this sample size; however, a larger sample size is recommended. These elite female hockey players demonstrated very high compliance with commitment and motivation to follow the programme. The increased number of hours that were spent in intervention period one (+860hrs) and intervention period two (+394hrs) may have contributed to the results. The biomechanical data in this study was based on fewer participants than the performance data (pre-test = 16 participants) and 10 participants at week 25 of the initial intervention period (1 player retired and 6 were unavailable).

Barboza et al. (2019) conducted a quasi-experimental study of the effect on injury rates of a hockey-specific warm-up among mixed youth club players (135 and 156 players in the intervention and control groups respectively, all 10 – 17 years old). The 12-minute, three-part intervention was designed for use before training and games. The first part, which was the preparation phase, involved agility and a cardiovascular warm-up. The second focused on movement skills such as speed and strength in hockey situations. The final aspect was a hockey skills section that included speed and strength exercises. Also, this warm-up was progressive over an extended period (40 weeks) and was supported by a mobile application. Following the intervention, the overall injury rates were 4.09 injuries per 1000 hours for the intervention group and. 6.44 per 1000 hours for the control group. Lower-extremity injury rates were similar, and the mean time-loss was 4.45 days for the intervention group and 4.13 days for the control group. The non-contact injury rates were also non-significantly different (1.95 vs. 2.88/1000 hours played). There was a high adherence rate (median = 84.3%) and although no statistically significant difference, the authors suggested that there was a meaningful difference between the two groups. One interesting observation was that the intervention was implemented and reported by club staff (coaches) rather than by independent researchers. The content of the warm up in the control group was prescribed as they continued to perform their own warm up, therefore, some exercises that protected the intervention group may have also been performed by the control group. Furthermore, the allocation of teams into groups was not randomised. Instead, the teams were assigned to the intervention group if they were interested in implementing the programme. These limitations may have affected the findings.

2.8.4 NMT and hamstring injury reduction

Hamstring injuries are common among players of team sports (see section 2.4). Some of the risk factors for hamstring injuries include active eccentric lengthening that occurs during the terminal swing phase of fast running, kicking, tackling, sidestepping and stretching (Opar et al., 2012), as well as age, previous injuries and isokinetic imbalances (Freckleton et al., 2014; Navarro et al., 2015). NMT programmes to reduce the risk of a hamstring injury, by either increasing hamstring strength or through correction of imbalances in hamstring/quadriceps ratio and bilateral asymmetry, have been investigated (Arnason et al., 2008; Zebis et al., 2015).

Croisier et al. (2008), in a prospective study of 462 professional football players, found that of 35 players who had sustained hamstring injuries, more had untreated strength imbalances and therefore were classified as having a higher risk of hamstring injury than those with no imbalance. In a randomised controlled trial study by Mediguchia et al. (2015), a seven-week NMT programme was recommended to 60 amateur male football players (aged 20-25 years). It included eccentric strength and plyometric exercises in the first of the weekly sessions and eccentric strength and acceleration exercises in the second week, to be conducted alternatively week by week. This intervention produced small changes in quadriceps strength but moderate changes in concentric and eccentric hamstring strength; therefore, a substantial change in hamstring/quadricep ratio. There were no significant differences in sprinting versus a control group (Mendiguchia et al., 2015).

A three-year prospective study of 24 female, professional football players (mean age 21.7 years) monitored injury rates during a control (usual practice) and an intervention season (including balance, coordination and balance-board training). The rate of non-contact hamstring injury was significantly reduced by 14.2/1000 hours with a significant reduction in time-loss for all injuries (from 14.4 to 1.5 days) during the intervention period. The reduction in the numbers of injuries was significantly correlated (r=-0.267) with the duration of the balance training periods (Kraemer & Knobloch, 2009).

2.8.5 NMT and knee injury reduction

There has been considerable research into the prevention of or reduction of knee injuries, and specifically ACL injury. Of the high-quality RCT studies that have been performed, all but one tested an intervention with female participants (Olsen et al., 2006). Most investigated NMT of soccer players (Gilchrist et al., 2008; Heidt et al., 2000; Kiani et al., 2010; LaBella et al., 2011; Mandelbaum et al., 2005; Söderman et al., 2000; Steffen et al., 2008; Waldén et al., 2012).Two studies investigated NMT that was applied to a mix of sports including football (Hewett et al., 1999; Pfeiffer et al., 2006b); some investigated its application to handball players (Myklebust et al., 2003; Olsen et al., 2005; Petersen et al., 2005); and finally, one investigated NMT with floorball players (Pasanen et al., 2009). Most of the interventions were multi-component and incorporated the recommended strength, plyometric and balance components (Monajati et al., 2016; Sugimoto et al., 2012) except in the study by Pfeiffer et al. (2006), who implemented only a plyometric training programme. Most (8/14) included verbal feedback. Other similarities in the data collection variables included age of the participants, who were in their mid to late teens except in three studies (Myklebust et al., 2003; Pasanen et al., 2009; Söderman et al., 2000) in which participants were in their early 20s. Most of the interventions were of 20-minute duration, except in the studies by (Hewett et al., 1999), who introduced a 60–90 minute intervention, and that by Heidt et al. (2000), who used a 75-minute intervention. Each intervention was performed two or three times per week. The time period for each intervention varied from pre-season only, through seven weeks and consecutive additional pre-season sessions, to once per week during the season.

The overall reduction in ACL injury was 17.2 – 17.7% for each of the influential factors, these were age, dosage, exercises used and whether or not feedback was supplied (Sugimoto et al., 2016). Those in the mid-teens (14 – 18 years old) showed the greatest reductions in numbers of ACL injuries. The dosage of sessions to achieve up to a 70% reduction in the number of ACL injuries was found to be sessions of between 20 and 30 minutes, twice per week for a season (Sugimoto et al., 2016). Analysis of neuromuscular programmes that reduced the incidence of all injuries indicated that a training frequency of two or three times per week for up to 15 minutes per session produced the greatest prophylactic response (Steib et al., 2017) for at least six weeks (Zech et al., 2010). Some studies reported low compliance as a limitation to the success of the programme; knowledge, understanding and perception of NMT were barriers. The effect on performance was inconclusive and is discussed in section 2.8.7.

2.8.6 NMT and ankle injury reduction

The occurrence of ankle injuries is common in team sports, especially in those that involve landing such as volleyball, netball and basketball (Section 2.4.7). Interventions to reduce the frequency of ankle injuries have been reported to be efficacious and usually include multi-intervention, balance and proprioceptive training sessions (Caldemeyer et al., 2020). Furthermore, balance (postural sway) has been used as a predictor of the occurrence of ankle sprains (de Noronha et al., 2006). Pooled ankle-sprain injury rates have been reduced following NMT (RR = 0.64) and a non-significant risk reduction for injuries overall (RR = 0.49) has been reported (Hübscher et al., 2010). Balance and proprioceptive training of male and female volleyball players was found to reduce significantly the risk of an ankle injury and ankle sprains for those who had already sustained this injury (Verhagen et al., 2004). The reduction may have been due to the positive effect of such training on joint position sense in all planes and postural sway (Taylor et al., 2015).

Although these collective results indicate that the use of NMT has a preventative effect on an ankle injury, other studies report mixed results. Emery et al. (2005) and McGuine & Keene (2006) reported significant reductions in the number of ankle injuries whereas Emery et al. (2007) did not. All these studies involved high dosages of NMT sessions (20-30mins, 3 / week) and substantial intervention periods (at least 6 weeks). Balance training, with or without other facets of NMT, has been reported to be particularly effective for those who have a recurring ankle injury (Vriend et al., 2016). Holden et al. (2016) concluded through a systematic review that there was moderate evidence of the preventative effect of NMT on the occurrence of ankle injuries.

2.8.7 NMT and performance

The effect of NMT on performance is less clear than it is on injury prevention. Comprehensive NMT appears to improve most components of fitness in team-sport players (Chappell & Limpisvasti, 2008; Lephart et al., 2005; Myers et al., 2005; Noyes et al., 2013). It is possible that when NMT is focused on a single outcome, the result in performance is equivocal. Vescovi and Van Heest (2010) undertook a study that involved female soccer players who completed the Santa Monica prevent injury and enhance performance programme which included a general warm up, stretching and lower extremity strengthening. The results indicated some improvement (non-significant) in straight-line speed with no difference in jump height or agility between the intervention and control groups even after three sessions per week for 12 weeks. Similarly, after balance training, balance-based test results were improved, but sprint and strength performance was not (Filipa et al., 2012; Zech et al., 2014). Both of these studies focussed on balance and core stability in female youth team sport players rather than lower extremity strength and plyometrics.

More investigation is required of the effect of NMT on team-sport performance, as results to date conflict. After 10 weeks of the ‘11’ programme, no differences were reported in strength (of quadriceps, hamstrings or hip add/abduction), vertical jump height, sprint or football-specific tests between the intervention and control groups (Steffen et al., 2008). This may be due to the lower intensity and duration of the programme compared to Hewett et al. (1999) and Myer et al. (2005) who both implemented 60+ min programmes. Conversely, in hockey that involved elite players, strength was maintained with significant improvements in 10-metre sprint times and aerobic power (Weir et al., 2019). Performance improvements may also be related to compliance; Weir et al. had very high compliance (88%) as well as engagement, motivation and commitment whereas Steffen et al. reported 73% (mean) compliance.

2.8.8 NMT programme adherence

Compliance with the programme, within groups and by individuals, is important. Reported compliance rates vary between 10.7% (Steffen et al., 2008) and 100% (Heidt et al., 2000). This variation has led to stratification of compliance rates; high compliance is defined as >66.6% for all sessions, moderate as 33.3 – 66.6% and low as below 33.3% (Sugimoto et al., 2012). The RR for ACL injuries with low compliance is 0.88, with moderate compliance is 0.56 and with high compliance 0.18 (Sugimoto et al., 2012). This pattern is also seen in studies that have reported all injuries.

The injury rate for those who performed the FIFA 11+, which reported high compliance, was 35% lower than the figure for those who followed a programme with intermediate compliance, and the difference was greater for acute injuries (Soligard et al., 2010). This pattern has been highlighted by a study that focused on adherence rates, in which the high-adherence group showed greater scores on the Star Excursion Balance Test (SEBT) and longer single-leg balance scores than the low-adherence group, while single-leg triple-hop performance was maintained (Steffen et al., 2013a). The role of the coach is important in terms of adherence and therefore the incidence of injury reduction (Emery et al., 2015). Therefore, suggested strategies for implementation include discussion and practical work with coaches regarding the programme to increase their knowledge, rather than simple dissemination of information (Bizzini et al., 2013).

2.8.9 Importance of feedback in NMT delivery

Feedback during NMT appears to enhance the preventative effect. This element was included in several studies such as that performed by LaBella et al. (2011) and is supported with evidence from the study by Myer et al. (2013). The latter, in a double-blind RCT, showed that with augmented feedback, peak knee abduction was reduced significantly more in the intervention group than in the control group during tuck jumps; the decrease of angle was 6.9° and 6.5° in the right and left legs respectively in the intervention group (which included feedback with the exercises). The control group (for which the coach led the exercises but provided no feedback) the reduction was much smaller (right leg = 2.9°, left leg = 2.7°).

Explicit learning is delivered with and internal focus and specific instructions for the joints involved. Implicit learning, in contrast, occurs with an external focus (Benjaminse et al., 2010). The exact processes are still unclear (Benjamisne et al, 2010). Part of the reason an internal focus is less beneficial compared to an external focus is the attempt to consciously control movement. This may interfere with normal, automatic motor control. Explicit learning is also less resilient to psychological and physiological pressure, interfere with normal automated processing of a motor schema when a quick response is required (i.e. during quick actions such as landing and sidecutting). This was demonstrated via a jump-landing task comparing an internal and external focus instructions. Welling et al. (2016) reported that both males and especially females should improved jump-landing technique and retention with a maintenance in performance for both genders. This research shows that external focussed instructions potentially could reduce ACL injury.

Other feedback mechanisms have been investigated, such as visual feedback. In a double-blind RCT, male athletes who received feedback significantly reduced their vGRF and increased knee flexion (both P<0.05) compared with controls who did not, and female athletes who received verbal feedback significantly increased knee flexion (P<0.05) compared with controls and achieved a non-significant reduction in knee valgus compared with controls (Benjaminse et al., 2015). The evidence from this study also suggests that these motor-learning strategies could be an effective method in altering kinematics and kinetics during a side-cutting task to reduce the occurrence of ACL injuries. Furthermore, Welling et al. (2016) and Benjaminse et al. (2015) demonstrated in landing and side-cutting tasks that modifications could be improved by feedback, especially with an external focus (the use of the unconscious and automatic processes) compared with an internal focus or control group, whilst performance was maintained.

2.8.10 Summary - neuromuscular training

There are many research recommendations that inform the content and implementation of NMT interventions to reduce injury rates and enhance performance. The multi-intervention programmes that include strength, proximal control, plyometrics and balance elements appear to have the greatest effect on overall injury rates. There is evidence from high-quality studies that NMT can also considerably reduce the occurrence of hamstring, knee (including ACL) and ankle injuries, especially among female athletes. Further, Wordeman & Hewett (2016) concluded that NMT was the "only effective tool" to reduce the number of ACL injuries (p.9).

The recommendations pertaining to implementation suggest that there is a dosage effect; for the NMT sessions to be effective, participants must take part in at least three sessions per week for at least 20 minutes before either training or competition. The benefits appear to be maximised in supervised sessions with feedback that particularly shows an external focus. These recommendations were adopted within the intervention study that was undertaken as part of the work for this thesis (Chapter 5).

Several sports-specific neuromuscular warm-up routines have been developed for team sports. Most studies that have been performed of these were of high quality, based on a RCT design, prospective in nature and/or involved a control group. Several studies (Hopper et al., 2017; Kearney, 2019; Pasanen et al., 2008; Soligard et al., 2008; Zebis et al., 2016) reported statistically significant reductions in numbers of target injuries, and high compliance with the intervention. The hockey-specific warm-ups that have focused on muscle activation and biomechanical variables in elite women's hockey, with the aim of reducing the incidence of ACL injuries and improving performance (Weir et al., 2019), have been efficacious. In addition, a study that explored the effects of NMT on injuries among club-based youth players showed a reduced rate and burden of injuries (Barboza et al., 2019).

2.9 Summary of literature review

Injury prevention is part of a risk-management strategy to which players and coaches should contribute, not only achieve goals in performance and retain player participation, but also because all those involved with the team have a responsibility and a duty to reduce the incidence and severity of injuries.

Hockey is a high-intensity, intermittent, invasive sport that involves many repeated actions in a variety of directions and planes. The nature of the sport leads to injuries that occur as a result of contact (with stick, ball or other players) or without contact (non-contact). Most injuries occur to the lower extremities; however, a few studies have reported the frequency, nature, severity and mechanisms of non-contact injuries, especially among female players. Further investigation into this area is required and was the focus of chapter 3 of this thesis.

Despite the variety of reporting mechanisms, units of measurement and definitions, non-contact injuries (or preventable injuries) continue to occur in team sports such as hockey. Moreover, the inclusion of interventions in team sports, including hockey, demonstrates that their application can reduce injury rates and the occurrence of antecedents to injury. Injury levels can be reduced through the use of NMT processes that stimulate the cardiorespiratory, neural and muscular systems in a manner that prepares the players for the sport, increases movement capability and reduces the risk of injury. Before a novel intervention is developed and implemented, it is important to consider the warm-up process and current warm-up practice. Evidence suggests that the warm-up is often omitted or its duration is reduced dramatically. Conversely, there is some evidence that warm-ups in hockey are comprehensive at the sub-elite level; however, this may not be the case at all levels and in all areas.

The NMT, according to the literature, should include a temperature increase and exercises in mobility, balance, proprioception, muscle activation, cutting/change to lateral direction (both anticipated and unanticipated), plyometrics and agility. Therefore, this thesis introduces a novel warm-up that addresses concerns that have been identified within the published literature: it is accessible to all hockey players, i.e. it does not require any additional specialised equipment, and it does not impinge on training or match-performance time (20 minutes in length). The warm-up is accompanied by feedback (externally focused) on movement technique to achieve the outcomes. The proposed intervention involves technique improvement (multi-directional running, landing and cutting), activation of muscles (including co-ordination and timing) and a reduction in forces. These components are likely to contribute to improved technique, balance, strength and endurance in the muscles that contribute to stability.

The goal of the studies that were undertaken as part of this thesis was to address the knowledge limitations that have been identified in the literature review above. There is a need for further evidence that pertains to non-contact injuries in hockey and this is explored in Chapter 3. Also, there is a lack of information regarding the current practice and focus of NMT in hockey and this is explored in Chapter 4. Finally, there is a need to investigate the biomechanical effects of NMT among recreational female hockey players and this is addressed in Chapter 5.

2.11 Methodological considerations

2.11.1 Introduction

The work that is described in this thesis has employed several different methodologies. The elements that underpin these approaches are discussed in this section. These approaches comprise a cross-sectional injury survey, warm-up practice observations, and a controlled study that includes measures such as EMG, kinematics and kinetics. This section covers each study in order and the methods of data collection that were used.

2.11.2 Study 1: Epidemiological approaches

The two main approaches in epidemiological research are prospective and retrospective studies. Prospective data are often those that are provided by doctors, physiotherapists or trained personnel soon after an incident has occurred. Retrospective studies involve the recall of the occurrence of injuries over a given period. Junge and Dvorak (2000) examined differences in data that were collected prospectively with an examination by a physician after one week and retrospectively in the same group. The number of injuries that were reported varied significantly: 558 injuries via the prospective method, 164 via the one-week retrospective method and 64 via the one-year retrospective method. Therefore, the accuracy of the retrospective data was questionable, which dramatically affected the injury rates that were reported. In the same study, data on severity showed that some time after the injury, players overestimated the time-loss they had undergone, as prospective data showed that more than half the injuries were recorded as ‘mild’ compared with the retrospective data, which showed that more than half the injuries were ‘severe’. However, the two data collection methods showed the same proportion of injury mechanism and body parts that had been injured (Junge and Dvorak, 2000).

Gabbe et al. (2003) also found issues with injury recall accuracy. They found, after a 12-month delay, that 80% of players of Australian Rules Football could recall accurately the number of injuries that they had suffered and the body parts that had been injured, but not the diagnoses, whereas only 61% could accurately recall all the information. Additionally, it appears that, as the level of detail increased, the level of accuracy decreased (Gabbe et al., 2003). The accuracy of sport-injury data has been shown to be improved with the introduction of a concurrent injury-prevention programme (Ekegren et al., 2014).

Where possible, prospective cohort studies are recommended (Hägglund et al., 2005). However, implementation in community settings poses difficulties and it is in this setting that the greatest study increase is recommended (Ekegren et al., 2016).

2.11.3 Questionnaire design, data collection and implementation

The accuracy of the collected information varies in other ways too. The data collection personnel and the size of the form were two variables that were investigated by Finch and Mitchell (2002) in a study that involved sports medicine clinicians over two years and more than 8000 cases. Two forms were completed by both the patient and the practitioner (each completed 50% of each form). The first form was two pages in length, completion was compulsory (with financial incentives over 12 months), and omissions of data were not allowed. The other form was one page long, completion was voluntary (with no financial incentives), data were collected over four one-week periods and omissions of data were allowed. The results showed large differences between the datasets, with considerably more injuries having been reported and in much greater detail through the use of the first method. However, data that were provided on the site of injury were similar in both methods (e.g. injuries to the knee were (method one - 36.2, 37.2% for method two). There was large agreement between the methods concerning the cause of the injury, but there were also some significant differences (e.g. injuries caused by being struck by a person = 13.7% in method 1 and 7.5% in method 2).

The accuracy of the data may be influenced by using system implemented. Finch et al. (2014) suggest that, when a classification system is used (in this case, the Orchard sports injury classification system was used), a greater agreement is found. The coders largely (95%) agreed on injury location (the first character) and the pathology (the second character). However, as the detail increased, inter-observer agreement decreased. Therefore, methodological differences could produce a variation in results, but the conclusions that were drawn in this study from the results produced by each method were similar (Finch and Mitchell, 2002).

Most of the settings that use codes for injury recording are professional sports venues, most of which are in football or related sports; there is no community-based system outside the USA (Ekegren et al., 2016). Furthermore, only seven of 15 of the systems have reported results that pass quality tests. Of the systems that have been evaluated, the NCAA ISS in football (soccer) captured 88% of the injuries in the test cohort (Kucera et al., 2011). The correlations between the medical staff report and player interviews were 0.99 for body part, 0.97 for injury type, 0.89 for the mechanism of injury and 0.61 for severity (Bjørneboe et al., 2011). Therefore, even in a professional environment, there are variations in the interpretation of sports injuries. In a community setting, there is a good correlation between trainers and players' perceptions of the injury, ranging from a 1.0 ('perfect') correlation for activity at the time of injury to 0.32 ('fair') for an expected date of return to sport (Ekegren et al., 2015). Furthermore, there is evidence that the quantity of injury data that is collected depends on the personnel involved. Yard et al. (2009) found that all athletic trainers participated in the injury surveillance study and submitted 96.7% of exposure reports compared with 43% of coaches who participated and completed 36.5% of the exposure forms. There was a much higher correlation between the injury data reported by athletic trainers and parents through an internet-based parental reporting system (Schiff et al., 2010). A dearth of data could lead to inaccuracies and affect strategies for sports injury prevention (Ekegren et al., 2016).

The implementation of injury recording systems, especially for community-based sport, could have an impact on the accuracy of data collection. The transition from paper-based injury recording (Dick et al., 2007) to a more technologically advanced process, such as a short message service (SMS) (Ekegren et al., 2015) or an online system (Yard et al., 2009), may increase the frequency and accuracy of community-based injury recording.

To the author's knowledge, there are no published consensus statements on injury definitions for hockey or a standardised method of data collection. Furthermore, a specific investigation into non-contact injuries has yet to be published. Therefore, a bespoke questionnaire is required. The development of the assessment tool that was used for this study largely followed the steps described by Kazi & Khalid (2012).

Following a period of development and pilot work, the tool was tested for validity (content, criteria and construct validity) and reliability and, therefore, could be used with confidence. Kazi and Khalid (2012) state that the questionnaire should be simple, viable, reliable, precise, sensitive, and measure the issue under investigation.

2.12 Methodological considerations for observational research

Observational research can be defined as follows: “Observers follow the flow of events. Behaviour and interaction continue as they would without the presence of a researcher, uninterrupted by intrusion” (Adler and Adler, 1994, p. 378). Observational research can be performed in several settings (Edwards and Skinner, 2009) and used to analyse sports activity patterns (Veal and Darcy, 2014). The methodological issues that are discussed below will be considered under the above definition.

The methods used can be classified into two forms: overt (with the permission and knowledge of the participants) or covert (without the knowledge of the participants). Observational research can take place within the natural setting of those under observation (direct) or in a more artificial environment. Another approach is that of naturalistic observation, in which the observer is either a member of the group being observed (participant) or is separate — the complete observer as a complete outsider (Tenenbaum and Driscoll, 2005). Each method has its ethical and/or ecological validity considerations.

The issues in observational research include internal and external validity, selection bias and information bias. Moreover, there might be confounding effects, i.e. a variable that causes the effect is other than the original variable (Grimes and Schultz, 2002). Grimes and Schultz (2002) discuss how a type two error can occur when the presence of a researcher alters behaviour.

Observation of participants behaviour may be recorded when the participant is unaware to record true behaviour, or if they are aware of their behaviour but unwilling to disclose it (Jones and Gratton, 2005). There are several disadvantages to observational research. Firstly, the observer may misunderstand behaviour, particularly if the observer is inexperienced. Hence, more than one researcher (assuming high inter-observer reliability) is sometimes employed. The recording method may form a second disadvantage. An action may occur too quickly for the researcher to record it. Technology may be a solution in this case. Thirdly, the researcher may affect the behaviour to the extent that the researcher's involvement may invalidate an observation (Jones and Gratton, 2005). Fourthly, the further from natural is the setting, the greater the chance of changes in behaviour, which decreases the validity of the data. Also, the more public and unstructured the setting, the more conspicuous the observer may become. Lastly, the recording of data can be altered by observer bias (Jones and Gratton, 2005).

Other than the selection of the setting, pertinent considerations include what is being documented, the training of the observers, descriptive observations of the field, selective specific observations to grasp central aspects, and the decision regarding when the observation will end (Jones and Gratton, 2005). Furthermore, the role of the observer must be defined to participants so that the observer can remain in or near the field without causing a disturbance (Jones and Gratton, 2005).

2.12.1 Practicalities of and frequent mistakes in observational research

Before observations can begin, the data to be collected must be defined, including the number of times an action occurs or how it is performed. The sample of people who are to be observed must be defined and randomly selected. The researchers must decide how the data are to be recorded; this could be via video or audio, or the use of pen and paper. As with other methods, the process should be piloted to identify any possible issues (Gratton and Jones, 2005). A coding or note-taking strategy should be developed to capture the variables and enable the deciphering of them afterwards (Tenenbaum and Driscoll, 2005).

Mistakes that are made frequently by researchers include attempts to observe too much at any one time or in a single observation, which can lead to missed data points and, consequently, inaccurate observations. The influence of the observer on behaviour is not always considered and evaluated before the data-collection event begins (Tenenbaum and Driscoll, 2005). Also, the observer must watch a representative sample of participants to avoid skewing the data. Often, observational researchers do not take adequate field notes and over-rely on recall (Jones and Gratton, 2005). Lastly, a frequent criticism is that researchers often fail to see the full picture (Tenenbaum and Driscoll, 2005).

2.12.2 Recording methods and examples of observational data in sport

Most recording methods are in the form of video/audio recording alone, recording via pen and paper (with checklists that must be completed), or recording the action in periods. Time and motion analysis has long been used in sport including hockey (Spencer et al., 2004) but has been superseded by more technologically advanced systems such as the global positioning system (GPS). Coaching behaviours have been observed and tools have been developed to assist in this process (examples are the coaching behaviour assessment system (CBAS) (Smith et al., 1977) and the Arizona State University observation instrument (ASUOI) (Lacy and Darst, 1984, cited in Lacy and Goldston, 1990).

Observational research into warm-ups has also been undertaken in golf (Fradkin et al., 2003) and hockey (Avest, 2010). The data collection technique that was utilised by Avest (2010) consisted of recording actions every 30 seconds (with coding for each action) in the warm-up. The coding system enabled the quick annotation of the event so that the missing of actions could be avoided.

2.12.3 Influence of the researcher

The influence of the researcher on participants’ behaviour due to his/her presence is a concern; the magnitude of the influence may depend on the method utilised (Kawulich, 2005). In this study, ethical considerations limited the choice of methods that are discussed by Kawulich (2005). Study 2 of this thesis adopted a ‘complete observer’ perspective; the participants were aware of the observer and they gave their consent to be observed. To minimise the possible influence of the observer, the suggestions from Cotton et al. (2010) were adopted to limit the influence of the observer. The influence of the observer was a concern for Fradkin et al. (2001), who reported that participants may have performed extra warming up that was beyond their usual routine in the presence of the observers, or they may have avoided being observed by preparing for a game out of sight of the observer.

Other considerations are the perspective and background of the observer and the influence that this has on the data. Culture, age, gender, class and ethnicity all influence how each action is recorded (Kawulich, 2005). The level of education and the reason for the observation may influence the choice of data that are recorded. There is little research into the magnitude of this bias. In the case of this study, the background of the observer is described, and an intra-observer reliability study was performed to explore further the consistency of observation.

2.12.4 Observation methodological considerations

The main advantage of covert observation is the authenticity of the data. However, this approach is precluded by ethical implications. This concern may seem insurmountable and may lead to a requirement that a follow-up questionnaire be given to allow a participant to verify an observation. Reliability is a concern in this type of investigation; therefore, a reliability study may be required to investigate the influence of this concern in particular settings.

The researcher’s influence takes two forms, since the presence of the researcher may alter both coach and participant behaviour. It has been recommended that researchers blend in, adopt a friendly and detached approach to observations, and observe participants in their most natural environment (Gardner, 2000). The selection of participants can be randomised as in higher-quality studies.

These ethical and practical considerations were adopted during observations of the participants (hockey players). The selection of participants for Study 2 of the work performed for this thesis was randomised.

2.13 Methodological considerations in EMG, kinematics and kinetics

The final study that was conducted for the thesis employed three methods of data collection: EMG, three-dimensional motion capture (3-D), and force plate data. Each of these systems is considered separately and the nuances of each method of data collection are briefly discussed in this section. Following the discussion, the recommendations were adopted and used in the methodology and the data processing of Study 3 (Chapter 5).

2.13.1 EMG methodological considerations

In the study 3 described in chapter 5, the primary outcome measure was the magnitude of muscle activation, with a particular focus on key timepoints and events (initial contact and maximum knee flexion). This outcome was principally measured using EMG. EMG is "an experiment technique concerned with the development, recording and analysis of myoelectric signals. Myoelectric signals are formed by physiological variations in the state of muscle fiber membranes" (Basmajian and De Luca, 1985, p1). Surface electromyography (sEMG) measures the muscle-activation signal that causes force production and produces movement (De Luca, 1997). Recording of this signal and the associated movements and changes that occur over time is the key to the assessment of the effectiveness of interventions in clinical research (Lynn et al., 2018) and to investigate injury risk in sport (Zeller et al., 2003).

The use of EMG to measure muscle activity is the most reliable way in which to understand muscle activity during movement (Basmajian and De Luca, 1985) and to show the neuromuscular response to limb movement (Marshall & Murphy, 2003). The systems that are currently in use involve real-time Bluetooth transmission, a high sample rate (2000Hz) and low energy use and cost (Chang et al., 2012). Surface EMG has superseded fine-wire methods with no loss of reliability. A comparison of these methods showed a high degree of similarity between results that were obtained using each system for both the shank and for the more superficial muscles (Péter et al., 2019). This study measured just superficial muscular activity; therefore, the systems were deemed to be comparable without the need for the invasive fine-wire system.

There are, however, disadvantages to sEMG. This method is susceptible to crosstalk (Johnson et al., 2011). Furthermore, the method cannot detect the passive movement of muscles and there may be some migration of the muscle below the skin, which affects the magnitude of the signal (Konrad, 2006). Also, some muscles may cause electrode dislocation during movement (Konrad, 2006). Several of the issues that surround the reliability and validity of sEMG research can be limited by consistent and methodological rigour (including careful electrode placement) (Subbu et al., 2015).

2.13.2 Placement of electrodes

The consistency of the placement of the electrodes in EMG sensors is critical. There has been considerable investigation into the most appropriate placement method for sensors. The most commonly used guidelines are surface electromyography for the non-invasive assessment of muscles (SENIAM) (Hermens et al., 2000). The SENIAM guidelines state that the sensor should be placed on the most bulbous part of the muscle belly. All the sensor placements must avoid innervation zones, motor endplates and tendon zones, as signals from these parts are unreliable and alter the magnitude of the signal (Farina et al., 2001; Mertletti et al., 2001).

Other investigations into sEMG sensor placement show some agreement and some additional guidance. Sacco et al. (2009) support the recommended placement to measure the activity of the vastus lateralis and peroneus longus; however, they recommend slightly different placements for sensors to measure the activity of gastrocnemius medialis and tibialis anterior. Zaheer et al. (2012) suggest that the number of motor units for each muscle varies, as does the position of these along the muscle length. These authors recommend that sensors on the vastus lateralis should be placed two-thirds of the way from the centre of the muscle towards the distal tendon. Their study found that the rectus femoris and tibialis anterior muscles exhibited greater-yielding sensor sites towards the distal end of the muscle, as did the gastrocnemius medialis. The gastrocnemius lateralis had greater yields at the proximal end. The greatest yield for the study of hamstring muscles depended on the head; for medial heads at the proximal end, the best position was a third of the distance from the end, whereas, for the lateral head, several sites showed similarly high yields of motor units (halfway and a third of the way along the muscle length).

There is, however, some individual variation. Rainoldi et al. (2004) found that innervation zones for each muscle varied between participants. The variation of innervation between individuals could be 29mm or more (tensor fascia latae) and 11% (gluteus maximus). These findings emphasise the need to find innervation zones for each participant before the attachment of sensors. Furthermore, during dynamic activities, innervation zones can move by between 1cm and 2cm (Farina et al., 2001). These studies show the need for further investigation to confirm or otherwise identify the most suitable sensor locations for each muscle.

EMG placement is important in the detection of meaningful estimates of EMG variables. The SENIAM guidelines state that sensors should not be placed on innervation zones because the electrical activity will be greater at these points and not representative of the whole muscle (Mesin et al., 2009). Konrad (2006) points out that these sites have greater signal instability; however, the sensor is of a size such that it is difficult for the placer of the sensor to avoid the innervation zones of some muscles. Furthermore, as an activity is performed, the placement of a sensor changes in comparison with its position on a muscle underneath the skin. This may mean that at some point, the sensor is above an area that contains a high density of motor endplates.

2.13.3 EMG signal interference and skin preparation

EMG sensors detect very small electrical signals (microvolts, µV); therefore, the sensors can record signals from other sources such as cardiac, artefact, power supply and sensor cabling. This is of particular note when studying muscles on the trunk or shoulder; however, activity from lower-extremity muscles only was recorded in this study, so any interference was minimal. Moreover, interference can also derive from electrical energy (between 50Hz and 60Hz) (Konrad, 2006). Also, noise can derive from cabling for the EMG sensors, but a wireless system such as the Delsys Trigno Wireless System (size, 37 x 26 x 15mm), which was used in this study, does not have this problem.

Motion artefact is caused by the interface of the electrode and the skin and has a frequency of 0-20Hz (Delsys, p. 3). Delsys suggests that good skin preparation can reduce this noise. Baseline noise can stem from muscle contraction at rest, and any baseline electrical activity must be deducted from the overall signal to leave only the signal that is due to muscle activity (Konrad, 2006). Skin preparation to maximise signal quality, which involves hair removal and cleansing of the skin with cleaning pastes, fine sandpaper and/or alcohol wipes is recommended (Konard, 2006). These recommendations were followed in this study.

2.13.4 Filtering methods and normalisation

Several methods can be used to filter EMG data, such as average rectified amplitude, linear envelopes, and integrated EMG (Kamen et al. 1995, cited in Robertson et al., 2014). The relevant methods are discussed here. EMG frequency distribution is between 10Hz and 500Hz; the majority of the EMG signal falls between 10Hz and 250Hz (SENIAM, International Society of Electrophysiology and Kinesiology (ISEK)); therefore, most sensors are bandwidth-filtered accordingly. Some EMG detection sensors, such as the Delsys Trigno, limit the detection of frequencies automatically to these limits. Several further steps follow this process: full-wave rectification further smooths the data via additional filters to remove movement artefacts (e.g. a low-pass filter of 20Hz) (De Luca, 1997); and a ‘moving average’ (movag) calculates the area under the curve and produces an ‘average rectified value’ (SENIAM), although De Luca (1997) recommends instead the use of the ‘root mean square’, which represents the signal power and, therefore, muscle activation. The time window that is selected affects the amount of smoothing (the greater the time window, the greater the smoothing). Studies have used various time windows (epochs). The recommended time window to investigate activities in this study (i.e. relatively fast movements) was around 20ms (Konrad, 2006); likewise, DeLuca (1997) suggests 25ms for data that are collected at 1000Hz.

To compare EMG activity from the same muscle on different occasions or between participants, the signal must be normalised (De Luca 1997) in a manner recommended by the *Journal of Electromyography and Kinesiology* (Burden, 2010). There are several methods by which normalisation is performed, all of which are repeatable and meaningful (Halaki and Ginn, 2012). However, debate surrounds which normalisation process is the ‘best’ (Burden, 2010). The common methods are maximum (or submaximal) voluntary isometric contraction (MVIC), measurement of peak or mean activation levels during the task under investigation, and measurement of the peak-to-peak amplitude of the maxima (M-wave) (Halaki and Ginn, 2012).

Many studies have utilised MVIC (e.g.Ekstrom et al., 2007); some authors report results of around 200% MVIC (Jobe et al., 1984). This method was originally recommended by both the ISEK and the SENIAM study (Merletti et al., 1999 and 1999b, respectively).

More recently, however, the reliability of this method has been questioned. Reaching an MVIC might be difficult (Halaki and Ginn, 2012), particularly with participants who experience discomfort or pain or are injured in some way. It may not be achievable and since sporting activities are dynamic (Burden, 2008), this method is not recommended by some researchers (Clarys, 2000).

A direct alternative to MVIC is the use of an isokinetic contraction (Burden, 2008). However, this method is not recommended as there is little difference between this method and MVIC (Burden et al., 2003). Burden (2008) recommends the use of the reference contraction method, which uses the EMG signal from contractions that are 80% or less than MVIC to produce a more stable reference value. A common criticism of this method is that the effort required by each individual varies; for example, one person may find a given weight difficult to move but another may find it easy (Halaki and Ginn, 2012). Besides, relating a submaximal to maximal is inaccurate because the relationship is nonlinear (Anders et al., 2005).

A method that is increasingly used to normalise EMG data is the use of the mean or peak EMG signals that are produced during the same dynamic task - termed the mean dynamic method and the peak dynamic method, respectively. The latter has been evaluated as reliable (Albertus-Kajee et al., 2011). In a running task that measured lower-extremity muscle activity, it was found that EMG normalised to the MVIC during sprinting produced a good result (mean intraclass correlation coefficient (ICC) = 0.76) and that during the submaximal condition the repeatability was much lower (mean ICC = 0.52). Whereas normalisation to the dynamic peak was considered, the repeatability was similar to that of the MVIC (mean ICC = 0.72) with a smaller range. Furthermore, MVIC appeared to show a large degree of sensitivity. Normalisation to the peak appeared also to show lower intra-participant variability than that of the MVIC method. Therefore, these authors concluded that the peak activity was the most reliable and most sensitive method to use. More recently, Zebis et al. (2015), in a reliability study, compared the reproducibility of EMG when normalised by the use of two different methods, and found that normalisation to the peak EMG amplitude during a sidecutting task offered greater reproducibility than did normalisation to a maximal voluntary contraction (MVC). The interclass correlation coefficient for the semitendinosus and the biceps femoris was 0.861 and 0.963, respectively, for the peak EMG amplitude, in comparison with 0.532 and 0.609 (respectively) for the normalisation using the peak amplitude during MVC.

This method of normalisation has its limitations (Burden et al., 2008; Kuntson et al., 1993). However, further to the support that is offered by the studies above, Yang and Winter (1984), Burden et al. (2003) and Konrad (2006) suggest that the use of this method decreases variability and improves group homogeneity. Burden (2010) suggests that the utilisation of MVIC to normalise EMG signals has an advantage over methods that do not, but the reliability of the exercises and techniques that are used to achieve MVIC is dependent on many factors.

Multiple methods of normalisation are in use, while the support for each is mixed and the choice of method appears to depend on the priority of each study. Normalisation to the peak of each muscle in each dynamic activity was used in Study 3.

2.13.5 Methodological considerations in kinematics

Motion capture is a precise technique that has been used to measure human movement in several scenarios such as injury prevention (Pueo & Jimenez-Olmedo, 2017). There are several types of motion capture, including optical systems that involve tracking by cameras that record at an appropriate speed (depending on the movement), typically 100Hz to 500Hz (Pueo and Jimenez-Olmedo, 2017). Various authors (Cappozzo et al., 2005, Chairi et al., 2005 and Leardini et al., 2005) discuss stereophotogrammetry. Some inherent considerations concerning motion capture and some specific issues that surrounded the process in this study are discussed below: joint centre calculation, soft tissue artefacts and filtering.

2.13.6 Joint-centre calculation, marker sets and soft tissue artefact

The calculation of the position of the joint centre is critical in motion capture. It is a source of error and carries over to the calculation of joint angles and moments. The joint centre was often taken as half way between the medial and lateral joint markers and calculated by motion capture software (C-Motion, Visual 3D). The main sources of error are soft tissue artefacts (Frick & Rahmatalla, 2018). Despite these sources of error, Fiorentino & Blemker (2014) found that optics were more accurate than predictive methods (for example, a regression with ASIS distance, Davis et al., 1991) in a study in which the researchers compared the optical system with other systems (using dual fluoroscopy as a reference).

It is important to have accurate, reliable and replicable marker locations. Achievement of this is affected by the experience and practice of the researcher, but these locations can be reliably found through the performance of several steps. Firstly, technical reference frames (TRF) and segment coordinate systems (SCS) are needed. The SCS can be calculated via the calibrated anatomical system technique (CAST) (Cappozzo et al., 1995). This method utilises anatomical landmark and tracking markers. The latter have no specific anatomical locations. A standardised location of anatomical markers has been proposed by the International Society for Biomechanics (Wu et al., 2005). Such recommendations give information on the rotation sequence.

Markers are recommended to be placed on all body segments to calculate the centre of mass (Halvorsen et al., 2009; Havens and Sigward, 2015; Rabu and Baroni, 1999) including for the smaller body segments (head, arms and hands). In this study the combined centre of mass for the segments was taken as the body's centre of mass. This data, as recommended by Moir (2008), was subsequently used to calculate the hop height. Meanwhile, other marker sets include the Vicon Plug-in full-body marker set, GaitLab, and Peak Motus 2000 have been used. Some researchers who have not used small segment markers have reported an 18% difference between use and no use of these markers (Vanrenterghem et al., 2010). These authors also report that the inclusion of only the lower extremity in a measurement of the centre of mass could omit up to 46% of the total body mass. Gill et al. (2017) reported high correlations (r = 0.975-1.00) between the anterior-posterior and vertical trajectories of the centre of mass between the full-body and reduced models (lower extremity and trunk); however, the correlation of the medial-lateral trajectories between the models was much lower (r = 0.774-0.767). These findings were used in the decision-making process of the work covered in this thesis.

There are different marker sets for the pelvis; each has advantages and disadvantages. The CODA pelvis marker set and the Helen Hayes marker set are popular. The CODA marker set involves the placement of the markers on the left and right anterior superior iliac spine (ASIS) and the left and right posterior superior iliac spine (PSIS). The CODA pelvis has an inherent 17° anterior tilt. The Helen Hayes marker set has markers for the left and right ASIS and the sacrum. There are other pelvis models, including that of Visual3D (C-Motion) as a hybrid. This marker set includes the greater trochanter and the right and left iliac crest tubercles with the PSIS. There is some evidence that an extra marker on the sacrum can resolve a common issue, which is the problem that the camera's view of ASIS markers can be obscured by body segments or subcutaneous adipose tissue (Borhani et al., 2013). A hybrid pelvis marker set was used in this study, therefore, no inherent tilt of the pelvis. The full marker set that was used in this study is detailed in the methodology section.

Consistency of marker locations is important for both intra- and inter-study comparisons as well as to enable the use of the same TRF and SCS. Despite the research above, the accuracy of the data is dependent on the accuracy of the placement of markers via palpation, which, in turn, is dependent on the researcher's knowledge of anatomical landmarks. One potential difficulty in the placement of an anatomical marker is the presence of subcutaneous adipose tissue. Another source of error that can cause problems during data processing is the occlusion of one or more markers during movement. This is particularly pertinent for the anterior pelvis markers. Some researchers have used additional markers on the posterior as an alternative (Borhani et al., 2013; Vogt et al., 2003).

One of the most frequent problems for researchers in motion-capture-based biomechanical studies is the issue of soft tissue artefacts. Other sources of error, for example skin elasticity, are an issue and discussed by Miyata et al. (2003) and Cerveri et al. (2005). Global optimisation is the term for the application of joint restraints to combat soft tissue artefacts, but this method is not commonly used. The application of this method requires predetermination of the magnitude of the degrees of freedom, which may be a source of error. Soft tissue artefacts cannot be eliminated completely (Lu & O'Connor, 1999). Their effect is reduced if a limited number of segments is used (Capello et al., 2005) and it is more pronounced during the use of a large number of segments/whole body; therefore, it is recommended that double calibration should be carried out (Stagni et al., 2009).

Soft tissue artefact occurs for all markers including the lower limbs. The amount of artefact, its implications and its effect on movement varies. The standard deviation of measurements taken from markers on 2 participants following a total knee replacement has been reported to be up to 31mm, while that on the shank was 21mm, during stair-climbing up/down, sit/stand and extension tasks (Stagni et al., 2005). The consequence of this variation is that sagittal measurements are reliable but the frontal and transverse plane measurements must be treated with caution. The participants in the Stagni study were considerably older (60+ years) than those who are involved in most biomechanical studies; therefore, soft tissue artefact may be greater among those with increased adipose tissue.

2.13.7 Filtering and capture rate

The signal that is acquired from optical systems contains data with various frequencies. These data include ‘noise’, particularly that caused by soft tissue artefact. Human movement often occurs at lower frequencies than noise (Winter, 2009); therefore, these higher frequencies can be attenuated. There is a chance that ‘real’ data may also be attenuated during this process and this can have a significant impact on the kinematic parameter (Sinclair et al., 2013). Furthermore, the speed of each segment is not uniform, either between segments or across time (Chiari et al., 2005), and the amount of noise also varies; therefore, sometimes different cut-offs must be applied. For example, in a sidecutting task, the trunk moves at a pace that is different from that of more distal segments such as the ankle.

There are many types of filtering mechanism of different magnitudes, which affect the data in different ways. Common digital filters that have been used in this field are the Butterworth filter (second and fourth order, some bidirectional) and Woltring filters. Usual cut-off frequencies range between 6Hz and 20Hz. Several authors have used a residual analysis to determine cut-offs (Roewer et al., 2014). The optimal cut-off frequency establishes the point at which there is an abrupt increase in the residual

(Nagano et al., 2003). A residual analysis was performed (on Backcluster 1, RASIS, Right thigh 2, Right shank 1 and Right metatarsal 1) before a cut-off frequency was determined for this study. Additional methods the can be used to determine the cut off include the discrete Fourier transform (Giakas, 2004). A filter processes data both forwards and in reverse to avoid a time shift and some studies also used unfiltered data (Cignetti et al., 2009). In addition, other methods, such as padding, could be used to reduce the need for filtering.

2.13.8 Methodological considerations – kinetics (force plates)

Measurement of forces within biomechanics has been almost exclusively carried out using a force plate. Force plates have been developed from technology that was based on a single pedestal system with a strain gauge, through the use of which forces were measured, some accurately but some with large errors at the extremes. Some force plates are now produced that use piezoelectric technology (quartz crystals). These are common in sports science laboratories and are often embedded in the floor. Some force plates are fitted with Hall-effect sensors and magnets and some have embedded strain gauges. The latter two products are portable, more compact and less expensive than fixed, piezoelectric force plates. These can be used in the field or in more ecologically valid scenarios.

2.13.9 Piezoelectric force plates

Piezoelectric force plates have been used as a gold standard against which other systems are compared because of their high consistency (Pearson correlation coefficient of 0.99, (Rogan et al., 2013). Kistler force plates in particular are well known for their quality (Rogan et al., 2015; Silveira et al., 2017) in measurements of peak vGRF, it has been found that the greater the sampling rate (400Hz+), the greater the reliability (Hori et al., 2009). Calibration is carried out by the manufacturer and there is a calibration certificate.

2.13.10 Sampling frequency

Several sampling frequencies have been used in biomechanical research in sports. Investigations indicate that a frequency as low as 100Hz can be used (Vanrenterghem et al., 2001). Hori et al. (2009) suggest the use of a frequency above 200Hz, while Bartlett et al. (2007) recommend 500Hz+ and preferably 1000Hz. Some have recommended the application of more than 1080Hz for high accuracy (Street et al., 2001), while some have used up to 2000Hz (Bartlett et al., 2014). The key factor in the choice of sampling frequency is the precision of the measurement (Beckham et al., 2014) and the activity performed. For the work described in this thesis, the key factors were the precision with which the initial contact and the peak vGRF (and, therefore, the rate of force development) could be detected. Moreover, the frequency was required to be an integer of the other sample rates, some of which were determined by the manufacturer rather than the researcher.

2.13.11 Filtering

As discussed above concerning kinematic data, kinetic data also must be filtered and the effects on these data are similar. Bessel and Chebyshev are commonly used filters but the Butterworth filter is the most popular. Bessel and Butterworth filters have similar effects on the same dataset (centre of pressure - CoP), whereas the Chebyshev has a greater effect and the filtered data are found to be outside the expected range (greater distortion) in comparison with the other filters; thus, this filter is not recommended (Robertson et al., 2013). Bessel and Butterworth filters are recommended by Koltermann et al. (2018) and Derrick (2004). Furthermore, a second- or third-order Butterworth or Bessel filter is advised, as these produce flat paths (fewer deviations) of CoP data (Koltermann et al., 2018). Therefore, high-pass filters with cut-off frequencies are between 10Hz and 30Hz recommended (Koltermann et al., 2018). These recommendations were heeded in the work that was performed for this thesis, both to improve filtering and to avoid a bidirectional time shift. The cut-off frequency is another consideration, as Kristianslund et al. (2012) found significant differences in results when different cut-offs were imposed. It is suggested that the use of low-pass cut-offs may “obscure physiologically meaningful data” (Roewer et al., 2012 p. 468), which would result in artificially small measurements and potentially lead to a type 2 error (false negatives).

2.13.12 Summary – all methodological considerations

The information that is presented in this section influenced the choice of methodology that was used in each of the studies that were performed as part of this thesis. The cross-sectional survey of injuries used in this thesis (Chapter 3) is a retrospective study with known limitations and advantages. Following the development of the study plan and pilot testing, a validation process was undertaken to ensure validity and reliability.

The observation of warm-up practice (Chapter 4) was conducted by use of an overt approach, mainly for ethical reasons, with a follow-up questionnaire against which the observations could be substantiated and to provide greater insight. The evaluation of the effects of the NMT programme (Chapter 5) was performed through the collection of EMG, kinematic and kinetic data. EMG data were collected with sensors that were placed on the lower extremity through the application of the SENIAM guidelines, which are supported in the literature. The choice of marker set for the kinematic variables was influenced by the variables that were desired, i.e. lower-extremity and centre-of-mass movements. Kinetic data were collected by the use of a force plate to assess the landing forces; due to inherent inaccuracies, however, no moment data were presented.

The novel aspects of this thesis are the investigation into the non contact injuries in Scottish hockey; the observation of current warm up practice across all levels with coaches perception and; the biomechanical analysis of a novel NMT female recreational hockey players.

Based on the gaps in the literature that have been described, the aims of the work that was performed in this thesis were to investigate:

1. Non contact injuries in Scottish hockey; the nature, severity and mechanisms of these injuries and the characteristics of those who sustain them (Chapter 3).
2. Current practice and coaches' perceptions of the warm up in hockey in Scotland (Chapter 4); and
3. The biomechanical (EMG, kinematics and kinetics) effects of a NMT programme on recreational female hockey players compared to a control group (Chapter 5).

Chapter Three: Hockey injury epidemiology (Study one)

3.1 Introduction

Injuries in hockey have been reported on extensively, and this section provides information on injury rates and the mechanism, severity and nature of injuries that occur in this unique sport. Although there have been a number of hockey injury studies such as those performed by Murtaugh (2001), Sharma et al. (2012) and Theilen et al. (2016), several have reported data from multi-sport events such as the Olympic Games and are focused on injuries that require hospital treatment, while one has provided more general injury-rate data from a multi-team hockey competition. Information on non-contact injuries that are sustained in recreational and elite hockey remains under-reported.

A wide range of injury rates, from 0.1 to 90.9 per 1000 player-hours, has been reported (Delfino et al., 2018). The injury rate at the recreational level ranges from 1.47 per 1000 athlete-exposures to 9.4 per player-hours and 15.2 injuries per 1000 hours of participation (Rees et al., 2020; Kerr et al., 2017; Stevenson et al., 2000 respectively); College players have been reported to be injured at a rate of 0.44 injuries per athlete-year (Murtaugh, 2001) and 3.7 and 7.9 injuries per athlete-exposure in practice and game situations respectively (Dick et al., 2007). Furlong & Rolle (2017) reported junior elite-player injury rates of 0.98 per match for males and females combined, whereas U21 females were stated to be injured at a rate of 70 per 1000 athlete-exposures (Rishiraj et al., 2009) and adult elite club players at up to 4.6 acute injuries per 1000 player-hours (Delfino et al., 2018). At the senior elite level, injury rates have been reported to range from 4.0 per 1000 hours for women (Junge et al., 2008) to 48.3 per 1000 hours for men (Theilen et al., 2016). This was compared to other team sports such as handball – 104.5 match hours with 16% being noncontact (Bere et al., 2015), football -20 per 1000hrs for sub-elite players (Whalan et al., 2018), lacrosse (men's) – 5.3 per 1000AE's (Kerr et al., 2017), floorball - 2.1 per 1000hrs (Pasanen et al., 2008).

There are a number of studies investigating injury epidemiology in hockey with a wide range of injury rates. Inter-study comparison is difficult as there are a number of units of measurement.

The range could be attributed to the context (level of play or only measuring match injuries). However, a specific investigation into noncontact injury rates has yet to be conducted.

According to Dick et al. (2007), non-contact injuries account for 26% and 64% of injuries in match and practice conditions, respectively; higher percentages (58.3%, 66.9% and 74%) have been reported for all non-contact injuries by Hollander et al. (2018), Rees et al. (2020) and Barboza et al. (2018) respectively. Theilen et al. (2016) suggest that there are fewer non-contact injuries among male elite players compared with females, and that in this population, between 2% and 7.1% of all injuries are non-contact. However, this pattern was not observed by Hollander et al. (2018), who found that the figure varied depending on the scenario (outdoor/indoor, match/practice). A much higher incidence of non-contact injuries – 41.5 injuries per 1000 athlete-exposures – has been reported by Rishiraj et al. (2009). However, these authors do not report details of the type or severity of these injuries. Likewise, in elite competition, non-contact injuries have been reported to account for 14% and 38% of all injuries for female and male players respectively (Junge et al., 2006). A higher figure of 41% has been reported for non-contact injury incidence in the Olympics (Engebretsen et al., 2013). In one study, Theilen et al. (2016) reported that 15% (male) and 20% (female) of all injuries were caused by tripping or falling and therefore could be considered non-contact. There is a wide variation of noncontact injuries which could be due to the different levels of play, context (match vs all injuries) and the specific type of hockey (indoor vs outdoor).

However, rarely reported in the literature details such as the injury site, the specific mechanism, severity and timing of the injury. Dick et al. (2007) have reported some of this information. This study shows that, in match conditions when the injury has caused 10 or more days of time loss, knee injuries account for 23.1% of all injuries and are caused by ‘internal derangement’. These injuries most commonly occur with no contact. The ankles are also frequently injured during games (equal third at 9.1% of all injuries), and ligaments are the most frequently affected area. These injuries are non-contact in nature. During practice, knee and ankle injuries show similar patterns (mechanisms and type of injury). Furthermore, injuries to the upper and lower leg occur more frequently as non-contact rather than contact and they cause muscle-tendon strains and stress fractures, respectively. In contrast, injuries to the upper body (notably the fingers and head) are most frequently caused by contact with the stick, ball or other players (Dick et al., 2007). Some details are also provided by Hollander et al. (2018). This study reported that 78% of non-contact injuries were contracted during practice and, in all contexts, over half the non-contact injuries occurred to the thigh (25.4%), lower leg and trunk (14.3% each).

There is a gap in the literature which focuses specifically on noncontact injuries (including rates, mechanism, severity, timing and nature of injuries as well as the characteristics of the injured) in field hockey. Therefore, there is a need for further investigation into the prevalence, mechanism, site, severity and types of non-contact injuries. The rate (per 1000 playing hours) and prevalence of non-contact injuries can be reported for these parameters. Thus, the lack of information that is available regarding non-contact injuries and current injury prevention strategies in field hockey warrants further research, which is the focus of this chapter of this thesis.

3.2 Aims and objectives for Study 1

Aim: To investigate the frequency of occurrence and characteristics of non-contact injuries in field hockey in Scotland.

Objectives: To conduct a survey to assess:

1. The frequency of injuries that are sustained in hockey
2. The characteristics of injured players
3. The mechanism of injuries
4. The nature of injuries that are sustained in hockey.
5. The timings of hockey injuries
6. The current injury prevention methods

3.3 Methods

The study was an online cross-sectional survey to explore hockey injuries in Scotland. An anonymous self-administered questionnaire (Appendix 3.1) was employed.

3.3.1 Study population and procedure

The questionnaire was open to hockey players of all ages and levels from November 2014 to March 2015, after institutional ethics approval had been granted (Appendix 3.2). The questionnaire was advertised for completion via the website of the Scottish Hockey Union (known as Scottish Hockey) and through posters that were displayed at communal hockey venues (Appendix 3.4). It was made available to all 99 registered clubs, which comprise approximately 7,000 registered members (response rate in this study was 4.9% of the registered population), in Scotland, either electronically via Survey Monkey (Survey Monkey™, San Mateo, CA, USA) or through the supply of a paper version (Online, n = 336, paper, n = 4) (Appendix 3.1). Participants were asked to recall injuries that they had sustained in the previous hockey season (2013–14).

3.3.2 Questionnaire development and characteristics

The injury questionnaire comprised of questions that enquired about a number of hockey injuries. It contained three sections and 21 questions. Section 1 consisted of questions that were related to the player's profile and the answers to which established player details, including the quantity of playing time (hours per week and weeks per year). Section 2 focused on non-contact injuries that had been sustained during the previous season. The facets that were considered included the injured body part, side of the body, the mechanism, timing (both game and practice), when in the season the injury had occurred, and the nature of the injury. The final part, Section 3, explored current training and exercise practice with a focus on conditioning both within and without the hockey training environment and the warm-up practice from the player's perspective.

The majority of the questions that were asked in this tool were closed questions. Two (the number of playing hours and number of weeks per year) were open. A further seven questions contained an option in which the participant could add additional information or answer with another option if none of the given answers were suitable.

The questionnaire was developed using a seven-step process (Table 3.1) that was proposed by Artino et al. (2014) and Gehlech and Brinkworth (2011). The process is summarised in Table 3.1. It was subsequently assessed for validity and reliability.

Table 3. 2 The validation and reliability process used for the hockey injury questionnaire

Step number	Step	Description
1	Questionnaire initial search	Search conducted for all previous injury surveillance literature
2	Initial development	Questionnaire developed based on previous injury surveillance forms
3	Initial piloting	Questionnaire piloted internally by the supervisory team; steps 1 – 3 repeated until ready for external piloting and comments
4	External pilot	Questionnaire available for external pilot and comments
5	Expert panel	Questionnaire tested for face validity (question and scale)
6	Expert panel assessment for reliability	Questionnaire tested for reliability (via correlation coefficient as recommended by Tsang et al., 2017)
7	Final version	Final version produced ready for completion by respondents

During step 1, desktop research was completed to gain knowledge and insight into the form, structure, and content of previous injury surveillance tools. A number of injury forms were considered in order to inform the questionnaire that would be used for this study. These included that developed by Junge et al. (2004), who investigated the occurrence of football injuries during FIFA tournaments. This form was also used subsequently to monitor injuries that occurred at the Summer Olympics of 2008 (Junge et al., 2009). Other methods and literature that informed the choice of the final method for this study were: the Orchard sports injury classification system (OSICS) (Rae and Orchard, 2007) and the discussion of the subsequent version (Orchard, 2010); the injury surveillance system of the NCAA (Kucera et al., 2011); raw data that was collected during injury surveillance at the 2012 Olympics in London (Engebretsen et al., 2013); hockey injury questions that were asked in a general injury questionnaire (Rishiraj et al., 2009); and a questionnaire regarding the lower back that was developed for female hockey players (Haydt et al., 2012). The Rishiraj et al. (2009) questionnaire implemented a modified sports/injury/illness reporting system (SIIRS) which, in turn, was a modification of the Canadian athletic injury/illness reporting system (CAIRS), which itself was developed by the British Columbia Athletics medical staff members; and the national athletic injuries/illness reporting system (NAIRS), which was developed by Pennsylvania State University.

After review of the existing questionnaires, it was decided that there was no existing questionnaire that was fit for the purposes of this study, so elements of published questionnaires were adapted. In steps 2 and 3, the internal review process was carried out until the primary researcher and supervisory team were satisfied that the questionnaire was suitable for step 4. During step 4, a feedback form was used during the external pilot in order to collate feedback from expert reviewers (see Table 3.2 below) while the validity and reliability process was conducted, as described below.

3.3.3 Validity and reliability process and results

Validation

During steps 4 and 5 of the process that is summarised above, the questionnaire was reviewed by expert reviewers. Validation was performed and the questionnaire was assessed using the content validity index (CVI), which included both the content (I-CVI) and answer scales (S-CVI), regarding relevance and comprehension. Each question was assessed by six experts (characteristics of the reviewers are presented in Table 3.2) as recommended by Rubio et al. (2003). The feedback form was adapted from one that had been developed by Gehlbach and Brinkworth (2016). Each question and all possible answers were assessed through the use of a Likert scale, with options that ranged from not understandable/relevant to extremely relevant/understandable (Appendix 3.3). Further comments could be included under each item. Following the results of this process, the questions and available answers were edited; for each question and possible answer to be included and/or remain unchanged in the final version, it was required to be 'understandable' and 'relevant' or better according to the judgement of each of the expert reviewers. A threshold of 80% was applied (Davis, 1992, as cited in Rubio et al., 2003). A summary of the results is provided in Table 3.4 and the full results are presented in Appendix 3.3.

Table 3. 3 Expert reviewer characteristics

Reviewer	Years in hockey	Hockey qualifications	Relevant experience
1	3	None	PhD and sports-science technician
2	50	FIH level coach	Academic, elite hockey player, hockey coach
3	25	Level 3	Elite player, elite coach, MSc sports-science student
4	55	Level 2	Olympic medal-winning coach, coach educator
5	35	Level 3	Academic, elite coach, elite player
6	2	None	PhD in psychology, research-methods lecturer

Reliability

A similar process to validation was implemented (as above) for reliability. An expert panel was assembled for this assessment. The panel characteristics are summarised in (Table 3.3).

Table 3. 4 Expert panel characteristics

Reviewer	Years in hockey	Hockey qualifications	Relevant experience
1	15	None	Current player, PhD sports science student
2	50	FIH level coach	Academic, elite hockey player, hockey coach
3	25	Level 3	Elite player, elite coach, MSc sports-science student

FIH: Federation of International Hockey

The results of the validation process (summarised in Table 3.4) demonstrated that the questions were both comprehensible and relevant. Further, the available answers were both comprehensible and relevant as they all exceeded the 80% threshold (Davis, 1992, as cited in Rubio et al., 2003).

Table 3. 5 Results of the validation process for the hockey injury questionnaire including I-CVI and S-CVI

Element	**Relevance**	**% (mean)**
Question comprehension	All relevant	95.2
Question relevance	All relevant	99.2
Scale comprehension	All relevant	96.8
Scale relevance	All relevant	98.4

Following the completion of the validation process, the reliability process was undertaken.

Questionnaire reliability

Reliability, in this context, is the consistency of results that are found via a test-retest process. It is used to calculate the extent of the consistency across time. The questionnaire was administered twice two weeks apart. This process was based on the principles that were established by Bolarinwa (2015). They are summarised in Table 3.5. The agreement between the test and retest results was then assessed by use of a Pearson product moment (Tsang et al., 2017). Previous researchers have used several threshold levels; an agreement level of 0.7 (Terwee et al., 2007) has been employed for large sample groups, whereas Helmerhorst et al. (2012) considered 0.4 to 0.8 to be moderate and acceptable, while greater than 0.8 was deemed strong. The hockey injury questionnaire (HIQ), which was developed for this study, was assessed for reliability by use of the process outlined below (Table 3.5); each reviewer (n = 3, characteristics in Table 3.3) was asked to complete the questionnaire based on the occurrences of the last hockey season and then to repeat the process two weeks later.

Table 3. 6 Summary of the reliability assessment

Step	Stage of process	Description
1	Initial completion of the HIQ	Each person within the process completes the questionnaire based on the last hockey season
2	A forgetting period	A two-week gap, after which the questionnaire is completed again
3	Second completion of the questionnaire	Each person completes the questionnaire again based on the same information in Step 1
4	Analysis of first and second completion of HIQ	Pearson correlation coefficient analysis of the similarity between completions 1 and 2*

*Using Statistical Package for the Social Sciences (SPSS) (IBM ®SPSS®, 2015, v23)

The results for this reliability test showed an overall agreement between the test and retest via a Pearson product moment (Tsang et al., 2017) that was performed in the software package Statistical Package for the Social Sciences (SPSS®) (IBM® SPSS®, 2015, v23). The resultant agreement between the test and retest was greater than 0.9 (individual results are provided in Table 3.6). Therefore, the HIQ was deemed to be reliable as the Pearson product moment was greater than that recommended by the authors above.

Table 3. 7 Questionnaire reliability results for each individual reviewer

Reviewer	Reliability*
1	0.997
2	0.996
3	0.902
Mean	0.965

*(Pearson product moment)

3.3.4 Summary of questionnaire development

This bespoke questionnaire was developed because no other epidemiological study had been focusing on non-contact injuries. This questionnaire was informed by the content of other injury questionnaires in the literature. Following development, the HIQ was subsequently found to be both valid and reliable after the implementation of established processes and therefore it was fit for purpose.

3.3.5 Eligibility, inclusion and exclusion criteria

The questionnaire was available between November 2014 and March 2015 for completion by any hockey player in Scotland who consented to take part in the study. The questionnaire was not available to those outside the geographical area (as determined by the district in the questionnaire). Completed questionnaires were excluded if questions regarding gender or hours or weeks of playing time were unanswered, or alternatively if the number of playing hours exceeded 25 per week or the number of weeks exceeded 52 if the hours and/or weeks were incalculable.

3.3.6 Data analysis

Following the transfer of data from paper forms and online to a Microsoft Excel® document, the eligibility and exclusion criteria were applied. Once complete, descriptive data were extracted and statistical analysis was performed in SPSS® (SPSS, version 23, IBM®, 2015) using a Mann-Whitney U test, the Kruskal-Wallis test for categorical data and a Chi-squared test for injury-rate data. An alpha level of ≤ 0.05 was applied for statistical significance. Injury rates were calculated as the total number of injuries divided by the total number of playing hours (practice and matches combined) and were expressed as the number of injuries per 1000 playing hours.

3.3.7 Severity of injury definition

The definition of injury was adapted from Fuller et al. (2007); consequently, injury categories were allocated as shown in Table 3.7.

Table 3. 8 Severity categorisation used in this study

Time loss (days)	**Injury category**
0-1	Slight
2-3	Minimal
4-7	Mild
8-28	Moderate
28+	Severe

3.4 Results

3.4.1 Sample

There were 340 respondents to the questionnaire, of whom 336 completed it online. The same instructions were provided for both the online and paper versions of the questionnaire. The researcher obtained consent to use participant’s data, who completed the questionnaire without any researcher input. Of the 340 that were completed, 33 were excluded for the following reasons: the gender or playing time questions were unanswered; the number of hours of playing time exceeded 25 per week, or the hours and/or weeks were incalculable. Following this process, 317 participants were included; of these, 166 were for male participants and 151 for females. The sample was broken down into player groups: 41.6% were defenders, 31.8% midfielders, 18.3% attackers and 7.3% goalkeepers. Less than 1% of respondents failed to specify a position (n = 2). There was a cross-section of hockey players across the performance spectrum, as summarised in Table 3.8.

The results show the injury rates that were reported for each of the participants’ body parts, genders, playing positions, ages and performance levels. Details regarding the injury mechanism, severity, nature, and timings are also included. The advice from coaches and each participant’s level of physical activity outside hockey were collated from answers in the final section of the questionnaire.

Table 3. 9 A breakdown of the respondents who were included in the study by position, level, age and experience – N (%)

Variable									
Age (yrs)*	Under 18	19 - 24	25 - 30	31 - 35	36 – 40	41 - 45	46 - 50	51 - 55	55+
N (%)	71 (22.3)	106 (33.4)	45 (14.2)	27 (8.5)	15 (4.7)	17 (5.4)	13 (4.1)	11 (3.5)	11 (3.5)
Level *#**	Summer only	District	Region	National	Inter-national	Masters only			
N (%)	16 (5.0)	105 (32.5)	70 (21.7)	93 (28.8)	25 (7.7)	2 (0.6)			
Experience (yrs)	1 year or less	2 – 5	6 - 10	11 - 15	16 – 20	21+			
N (%)	0 (0)	43 (13.5)	95 (30.0)	73 (23.0)	33 (10.4)	73 (23.0)			
Position **	Goal-keeper	Defence	Midfield	Attack					
N (%)	23 (7.3)	132 (41.6)	101 (31.8)	58 (18.3)					

*No response = 1 (0.3%), **No response = 3 (1%), ***No response 6 (1.9%)
#Some 41-45 respondents specified more than one level in their answers

3.4.2 Frequency of injury

In this study, 243 non-contact injuries were reported, of which 47.6% were to females and 52.4% to males. The injuries were predominantly to the lower body (which means the part of the body from the lower back to the feet). Injuries to this part of the body accounted for 87% of all non-contact injuries, while the remainder (13%) were to the upper body. Injuries to the knee, hamstring, ankle and lower back were the most frequently reported for both males and females (see Figure 3.1).

The frequency of injury for all hockey players was 4.09 injuries per 1000 hours (95% CI, 3.59-4.54). Females sustained injuries at a rate of 4.73 per 1000 playing hours (95% CI, 3.98-5.4) and males sustained injuries at a rate of 3.47 per 1000 playing hours (95% CI, 2.83-4.06). These figures covered all hours of playing, including training and competition. When scenarios were removed in which players had ‘no time off’ (i.e. the player did not miss any practices or matches), the injury rate was 3.63 per 1000 hours for all hockey players (3.98 for females and 3.24 for males). The Kruskal-Wallis test demonstrates that there was no significant gender difference (H(1) = 0.228, p = 0.633) for all injuries or when no-loss-of-playing-time injuries were removed (H(1) = 3.114, p = 0.078).

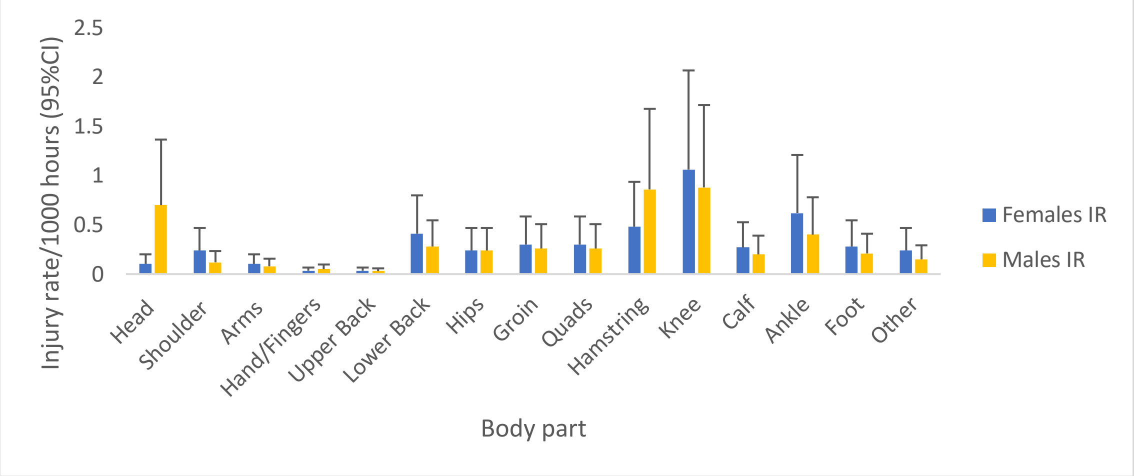

Figure 3. 1 Injury rates (IR) per 1000 hours for each body part (95% CI)

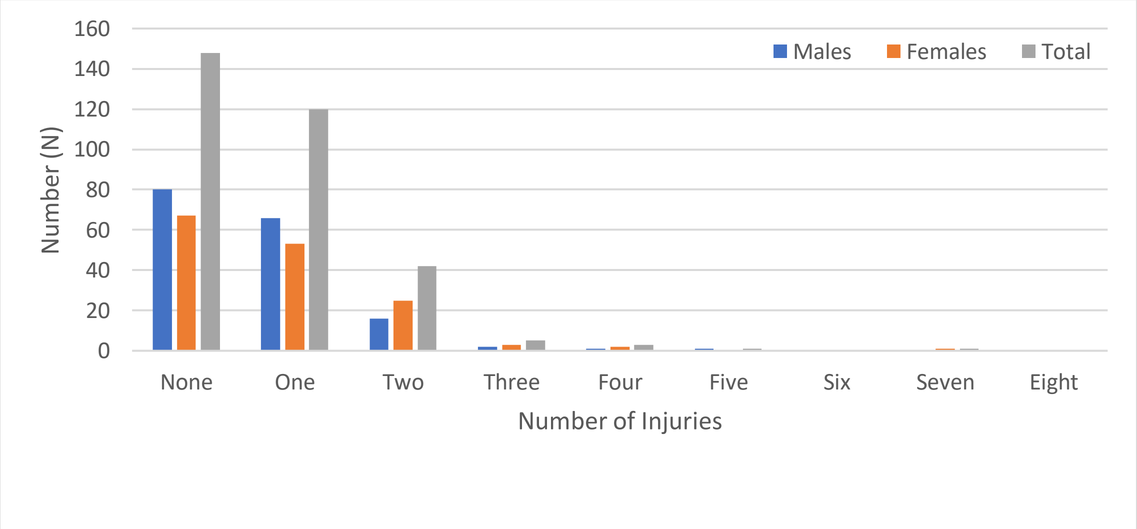

Figure 3. 1.1 The number of injuries sustained by each respondent (N)

3.4.3 Injury rates for each anatomical site

Several anatomical sites sustained non-contact injuries (Figure 3.1). The most frequently injured body site was the knee, at slightly higher injury rates for females (Table 3.9). The hamstrings were frequently injured, with slightly greater injury incidence in males. The ankles and lower back showed slightly lower injury frequencies in comparison with the hamstrings. These injuries showed a slightly higher frequency among females compared with males for both sites.

Table 3. 10 Selected injury rates for each gender

Body part	**Gender**	**Injury rate (per 1000 playing hrs)**	**95% CI**
Knee	Females	1.06	0.72-1.41
	Males	0.88	0.62-1.09
Hamstring	Females	0.48	0.26-0.73
	Males	0.86	0.64-1.07
Ankles	Females	0.62	0.37-0.90
	Males	0.40	0.26-0.56
Lower back	Females	0.41	0.22-0.65
	Males	0.28	0.17-0.42
Groin	Females	0.30	0.14-0.50
	Males	0.26	0.19-0.46

Overall, there were statistically significant differences in the injury rates between body parts (Kruskal-Wallis test, H(14) = 24.449, p = 0.04). Pair-wise comparisons suggest that several lower body parts were injured more frequently than those of the upper body. Injury rates to the groin, hamstring and knee were significantly greater or the rates approached significance in comparison with many of the upper body parts (Table 3.10). In this case, there was no significant difference between the genders (p = 0.633).

3.4.4 Injury rates according to playing position

A positional comparison showed that goalkeepers had a tendency to have the lowest injury rate at 2.5 injuries per 1000 playing hours (95% CI, 1.4-2.78) followed by midfielders (3.57, 95% CI, 2.6-4.2) and then defenders (3.57, 95% CI, 2.8-4.24). Attackers showed the highest injury rate (5.8, 95% CI, 4.4-7.2). The analysis of the positional differences showed that there was no significant difference (Kruskal-Wallis test, H(3) = 0.392, p = 0.392). The trend was towards a slightly higher injury rate for attackers compared with the other positions and a slightly lower rate for goalkeepers.

3.4.5 Injury rates according to performance level

A comparison of injury rates by performance level indicated no significant differences (Kruskal-Wallis, H(5) = 5.00, P = 0.416). The lowest injury rate (2.66 per 1000 playing hours, 95% CI, 1.7-3.6) was identified among the international players and the highest rate occurred among masters players (8.33, 95%CI, 0.21-32.56). There was no clear trend between level and injury rates.

Table 3. 11 Statistical differences between injury rates to body parts (genders combined)

Body part	**Test statistic**	**Std error**	**Std test statistic**	**p value**
Head-Groin	22.0	8.795	2.502	0.012*
Head-Knee	25.5	8.795	2.900	0.004*
Head-Hamstring	26.5	8.795	3.013	0.003*
Hand/fingers-Groin	18.5	8.795	2.104	0.035*
Shoulders-Knee	22.0	8.795	2.502	0.012*
Hand/fingers-Knee	22.0	8.795	2.502	0.012*
Shoulders-Hamstring	23.0	8.795	2.615	0.009*
Other-Knee	17.5	8.795	1.99	0.047*
Other-Hamstring	18.5	8.795	2.104	0.035*
Hand/fingers-Hamstring	23.0	8.795	2.615	0.009*
Shoulders-Groin	18.5	8.795	2.104	0.035*
Upper back-Groin	-17.5	8.795	-1.99	0.047*
Upper back-Knee	21.0	8.795	2.388	0.017*
Upper back-Hamstring	22.0	8.795	2.502	0.012*
Arm-Knee	20.0	8.795	2.274	0.023*
Arm-Hamstring	21.0	8.795	2.388	0.017*
Head-Foot	16.0	8.795	1.819	0.069
Head-Quadriceps	16.5	8.795	1.876	0.061
Head-Ankle	16.75	8.795	1.905	0.057
Head-Calf	17.0	8.795	1.933	0.053
Head-Lower back	17.0	8.795	1.933	0.053
Arm-Groin	-16.5	8.795	-1.876	0.061

3.4.6 Injury rates according to age

The age categories in the questionnaire were grouped together into a ‘young’ group, a ‘middle’ group and an ‘older’ group. The young (under 18s-25-year-old) group showed an injury rate of 3.6 per 1000 playing hours (95% CI, 3.03-4.11), the middle (26-40-year-old) group showed a rate of 5.3 (95% CI, 4.09-6.4) and the rate was 6.99 per 1000 playing hours (95% CI, 4.75-9.3) for the older (40-year-old+) group. An analysis of the injury rates suggested that the difference was non-statistically significant (Kruskal-Wallis, H(2) = 2.00, p = 0.368). However, a trend towards an increase in injury rate with age was evident.

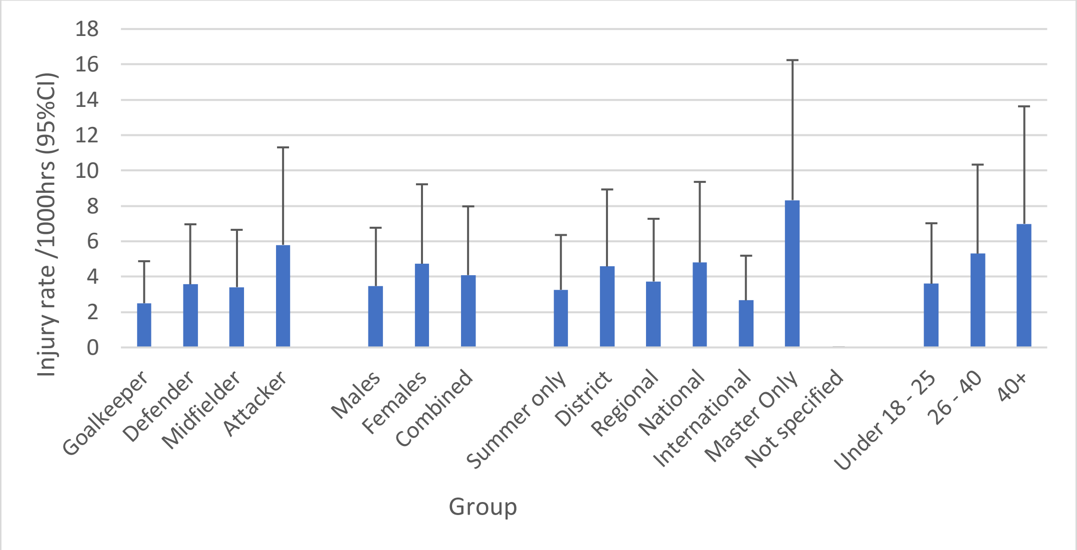

Figure 3. 2 Injury rates among males and females according to playing position, gender, professional level and age per 1000 playing hours (with 95% CI)

3.4.7 Mechanism of injury and side of the body

The most frequent mechanism of injury for all hockey players was changing direction or 'cutting' (19.6% or 26% if 'other' and 'not specified' options were removed from the data set), followed by sudden acceleration (13.8% (18.2%)), and landing (12.9% (17.1%)). The cumulative figure for 'other' was 28.5%. There were no statistical differences between the mechanisms of injury (Kruskal-Wallis test, H(8) = 8.00, p = 0.433). However, change in direction, landing and sudden acceleration were found to be more frequent injury causes than the other mechanisms. These injuries occurred on both sides of the body (40.3% to the left side and 42% to the right, with 16% occurring on both sides) for males and females combined. There were no differences between sides (Mann-Whitney U, p = 1.00), but there were more instances in which a single side was injured rather than occasions in which both sides were injured at the same time. Of the injuries that were sustained, 51.4% were index injuries and 48.6% were recurrent injuries (Figure 3.3).

3.4.8 Nature of injuries and timings of injury

Most of the incidents that were recorded in this study involved muscle damage (48.3%), which included muscle strains, sprains and pulls. Ligament injuries, including ligament breaks, sprains and strains, were also frequent (19.2%), while abrasions counted for 4.9% (Figure 3.3). There were no statistically significant differences between the types of injuries that were sustained by the respondent hockey players (Kruskal-Wallis test, H(8) = 8.00, p = 0.433); however, the graph shows a trend in that muscle and ligament damage was sustained more frequently than other types of injuries.

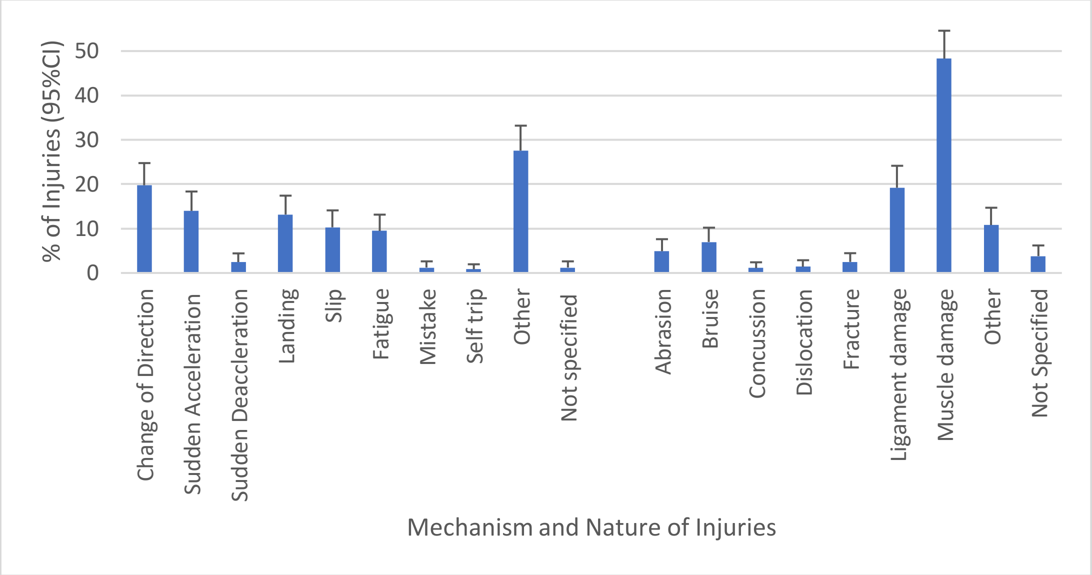

Figure 3. 3 Breakdown of the mechanisms and types of injuries for all hockey players (%)

3.4.9 Timings of injuries – during a game

Nearly a third (31%) of all injuries were sustained during training. Another 18.9% occurred during the third quarter of a game (minutes 35-42.5), 13.9% during the second quarter (minutes 17.5-35), and 11.5% during the first quarter (minutes 0-17). Nonetheless, there were no significant statistical differences between the times at which the injuries occurred during a game (Kruskal-Wallis test, H(8) = 8.00, p = 0.433).

3.4.10 Timings of injury – time of year

Injuries to players occurred throughout the hockey season; many more injuries (65%) occurred in the first half (pre-season to December) compared with the second half of the season (35%) (January to July). The months in which the most injuries were contracted were September, October and November (16%, 16.8% and 14.4%, respectively) (Figure 3.4). There was no significant difference between these figures (Kruskal-Wallis test, H(13) = 13.00, p = 0.448); nor was there a significant difference between the figures for the two halves of the season, despite the apparently large difference (H(1) = 1.00, p = 0.317).

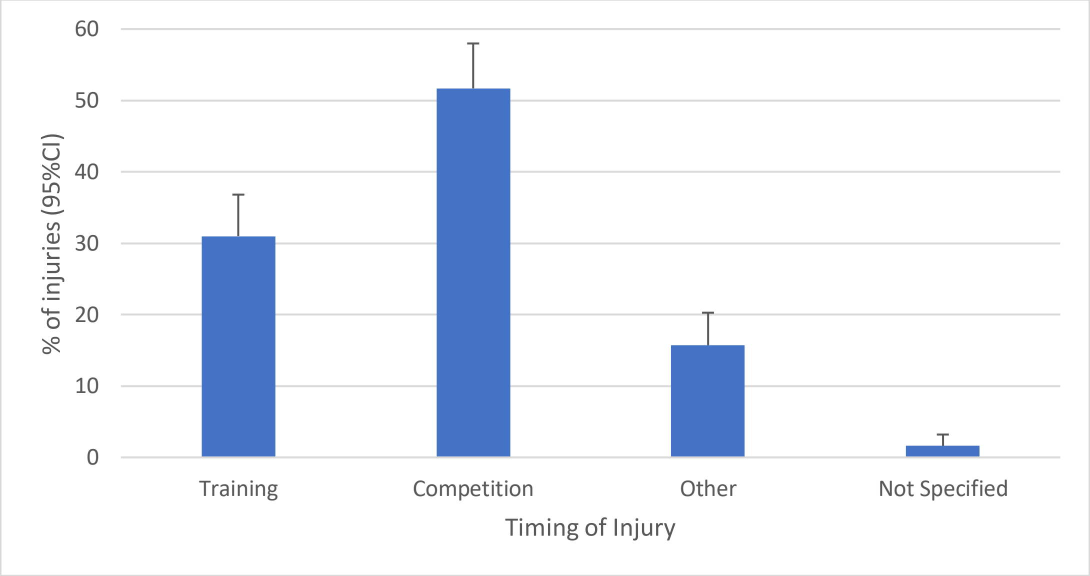

Figure 3. 4 Timing of injuries (%, 95%CI)

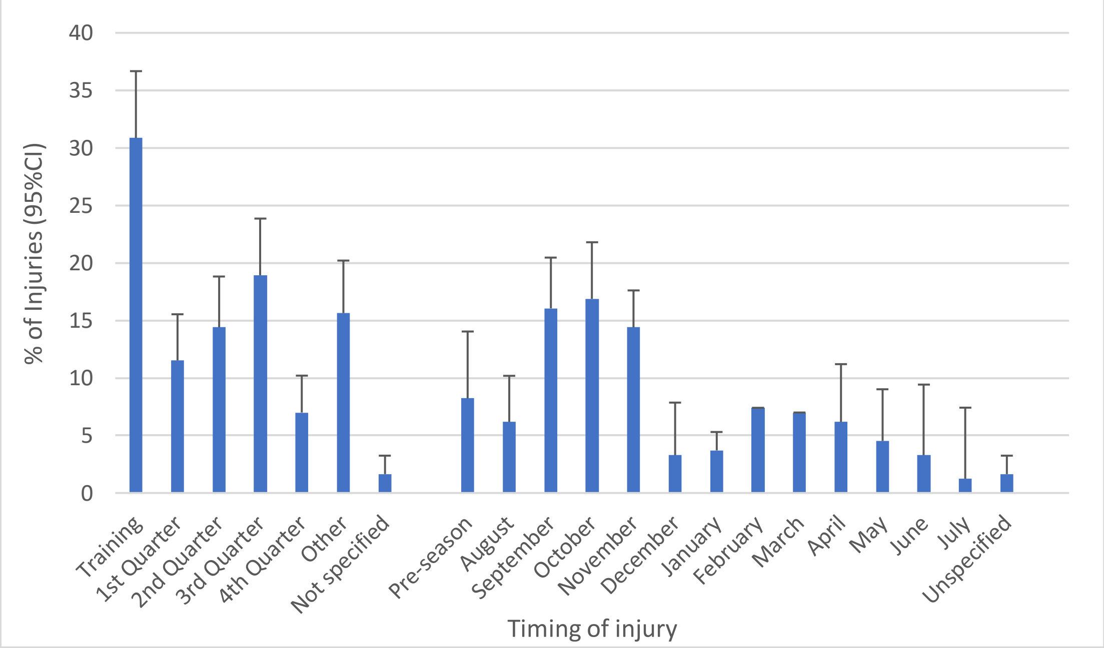

Figure 3. 4.1 Injuries sustained during games and in each month of the season, both in training and competition (%, 95%CI))

3.4.11 Severity of injury

Investigation of how much playing time was lost due to these injuries, or their severity, showed that 30.3% of hockey players (males = 16.7%, females = 37.0%) missed no hockey sessions after they had sustained an injury (after 'not specified' (n = 16) was removed from the data); 16.9% (males = 13.3%, females = 18.6%) missed the next session after the injury had been sustained; 13.5% (males = 16.7%, females = 11.9%) missed up to one week; 19.1% (males = 16.7%, females = 20.3%) missed two to four weeks of play; and 10.1% (males = 13.3%, females = 8.5%) had one to two months of time-loss (Figure 3.5). There were no gender statistical differences (Independent t-test, t_{14} (-0.326), P = 0.749, 95%CI = 17.036 – 12.537).

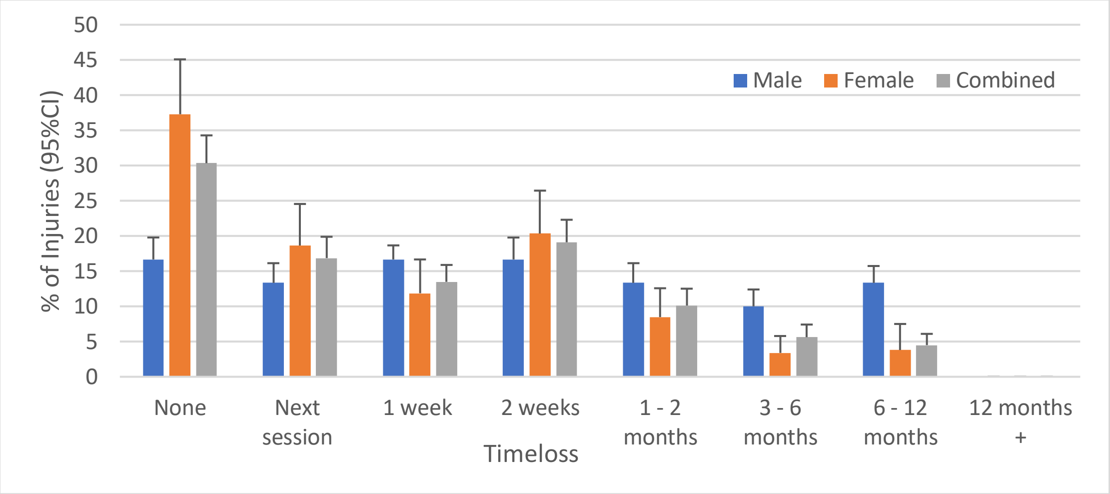

Figure 3. 5 Playing time lost due to injury for all hockey players (with no timeloss included) (%, 95%CI)

Figure 3.5 shows that most respondents reported that they suffered no loss of playing time due to their injuries. In these scenarios, although the participants reported that they considered themselves to be injured, they had recovered and were able to participate in the next hockey activity (training or match). The next most frequently reported loss of playing time was two to four weeks. This was followed in terms of frequency by those who missed the next event and then by those who lost playing time of one to two months. The latter accounted for 10% of all injuries.

Table 3.11 shows the collated data for all the elements of injury to lower extremity body parts in decreasing order of frequency. It is clear that the knee, hamstring and ankle injuries were the most frequent and that these typically involved ligaments and muscles. The most common mechanism of injury was landing and cutting in competition, and this type of injury most often caused several days of lost playing time (from 5 days to more than 100).

Table 3. 12 Collated information on lower-extremity injuries in hockey (*Top three most frequently occurring, so not all columns add up to 100%)

Lower body part	Caused by*	Overall N (%)	Injury sustained	Overall N (%)	Type of injury	Overall N (%)	Mean lost playing days (all)	Lost playing days (with removal of no time-loss)	When occurred	Overall N (%)
Knee	Cutting Landing Fatigue Slip	19 (36.5) 9 (17.3) 4 (17.7) 5.8 (5.8)	Ligament Muscle Abrasion Bruise	21 (40.4) 9 (17.3) 5 (9.6) 4 (7.7)	Acute Chronic Other	8 (15.4) 6 (11.5) 38 (73.1)	18.3	19.6 (35.3)	Training Competition Other	17 (32.7) 27 (51.9) 8 (15.4)
Hamstring	Acceleration Other Slip and Cut	23 (45.1) 9 (17.7) 7 (13.7)	Muscle Other	50 (98) 1 (2)	Acute Chronic Other	8 (15.7) 9 (17.6) 33 (66.7)	28	35.4 (63.8)	Training Competition Other	15 (29.4) 30 (58.8) 6 (11.8)
Ankle	Cutting Other Slip Self-trip	8 (33.3) 6 (25.0) 4 (16.7) 4 (16.7)	Ligament Muscle Other	18 (62.5) 4 (16.7) 2 (8.3)	Acute Chronic Other	6 (25) 2 (8.3) 16 (66.7)	37.5	63 (107)	Training Competition Other	7 (29.2) 15 (62.5) 2 (8.3)
Groin	Cutting Fatigue Slip	9 (47.4) 4 (21.1) 2 (10.5)	Muscle Ligament Other	17 (89.5) 1 (5.3) 1 (5.3)	Acute Chronic Other	26.3 26.3 57.9	5.5	4.3 (7.6)	Training Competition Other	7 (36.8) 9 (47.4) 3 (15.8)
Lower back	Cutting Other Landing	5 (29.4) 8 (47.0) 2 (11.8)	Muscle Bruise Other	11 (82.4) 2 (11.8) 1 (5.9)	Acute Chronic Not Specified	4 (23.5) 2 (11.8) 11 (64.7)	5.9	7.9 (15.4)	Training Competition Other	6 (35.3) 10 (58.8) 1 (5.9)
Calf	Acceleration Fatigue Other	7 (28.0) 5 (20.0) 8 (38.1)	Muscle Other Ligament	22 (84) 2 (8.0) 1 (4.0)	Acute Chronic Other	6 (16.7) 4 (33.3) 11 (50.0)	16.8	16.8 (17.6)	Training Competition Other	1 (4) 19 (76) 5 (20)
Foot	Self-trip Other Landing	2 (15.4) 5 (38.5) 3 (23.1)	Bruise Ligament Fracture	4 (30.8) 2 (15.4) 2 (15.4)	Acute Chronic Other	4 (30.8) 3 (23.1) 6 (46.2)	14	14 (12.2)	Training Competition Other	7 (53.9) 5 (38.5) 1 (7.7)
Quad	Acceleration Other Cutting Fatigue	6 (42.9) 3 (21.4) 2 (14.3) 2 (14.3)	Muscle Other Abrasion	10 (71.4) 3 (21.4) 1 (7.1)	Acute Chronic Other	5 (35.7) 0.0 9 (64.3)	10.8	10.7 (11.8)	Training Competition Other	8 (57.1) 4 (28.6) 2 (14.3)
Hips	Other Fatigue Cut/ Acceleration	6 (54.6) 2 (18.2) 1 (9.1)	Muscle Other Ligament	7 (70.0) 2 (20.0) 1 (10.0)	Acute Chronic Other	0 (0.0) 3 (27.3) 8 (72.7)	36.1	114 (134.5)	Training Competition Other	6 (60) 1 (10) 3 (30)

Table 3.11 shows the collated data for all the elements of injury to lower extremity body parts in decreasing order of frequency. It is clear that knee, hamstring and ankle injuries were the most frequent and that these typically involved ligaments and muscles. The most common mechanism of injury was landing and cutting in competition, and this type of injury most often caused a number of days of lost playing time (from five days to more than 100).

3.4.12 Actions in response to the chance of injury

An important finding that is shown by Table 3.12 is that most players did not adjust their playing style to protect their bodies from injury, to avoid injury or to avoid pain, meaning that injuries occurred as a result of playing 'normally'. The results also show that most players did not play indoor hockey during the outdoor winter break (75.6%) and most players did not complete a second pre-season (only 15.6% performed a 2nd pre-season) to prepare for the outdoor season (the outdoor season finishes at the end of November and re-starts approximately in February). These findings may be because their hockey playing was greatly reduced during non-playing periods.

Table 3. 13 Numbers of players who limited their playing style*

Response	**Limited playing style – protect N (%)[1]**	**Limited playing style - pain N (%)[2]**	**Limited playing style - to avoid injury N (%)[3]**
Yes (%)	41 (14.1)	42 (14.4)	43 (14.9)
No (%)	251 (85.9)	249 (85.6)	246 (85.1)

*Number – N (%) calculated from those that answered this question
[1]25 (7.9%) skipped this question, [2] 26 (8.2%) skipped this question [3], 28(8.8%) skipped this question

3.4.13 Exercise other than hockey

Respondents stated that they performed some exercise other than playing hockey. The predominant physical training outside the hockey training environment was cardiovascular training, stretching and balance workouts, while a small percentage of respondents completed some balance training or lower-body strength training (Table 3.13)

Table 3. 14 Training by hockey players other than hockey training sessions

Type of training*	% of participants	Type of training	% of participants
Balance	12.6	ME – weights – combo	5.2
Cardiovascular	18.8	Circuit or similar	3.3
Stretching	15.7	Strength – lower	10.4
ME[1] – sprints	6.5	Strength – upper	8.3
ME– weights – legs	8.8	Other	3.3
ME – weights – upper body	7.3	Total workouts	522

*Multiple answers available

[1] Muscular endurance

In terms of workouts that respondents performed outside hockey training, most survey participants stated that they performed at least two workouts per week, with most players performing between one and three per week. The mean number of workouts per week outside hockey training was 2.71 (SD 1.46, 95%CI, 2.5-2.92) (Figure 3.6).

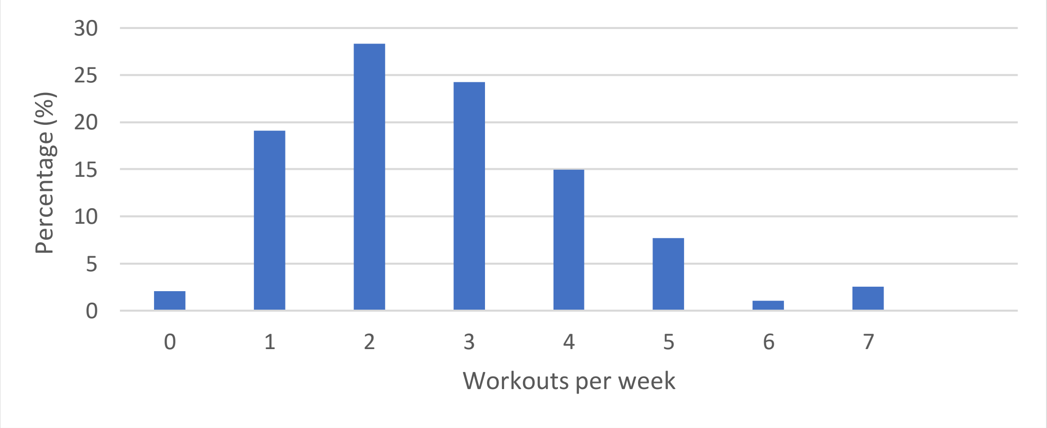

Figure 3. 6 Non-hockey workouts performed by hockey players (%)

3.4.14 Training during hockey sessions

During hockey sessions, most players performed some physical conditioning tasks (Table 3.14) and these predominantly consisted of cardiovascular training, muscular endurance (in the form of multiple sprints), or strength-based training. Balance training was the fourth most frequently performed type of physical training.

Table 3. 15 Types of physical training performed during hockey training

Exercise in hockey training	% of participants	Exercise in hockey training	% of participants
Balance	21.0	Strength	23.2
Cardiovascular	29.5	Other	1.3
ME – multiple sprints	25.0	Total (n)	301

The results of this study (from a total of 176 responses) showed a trend that the coach did not usually conduct the warm-up with the team; rather, the team captain or a person who had exercise experience conducted the warm-up, or alternatively the person in charge varied (Table 3.15).

Table 3. 16 Warm-up/cool-down leaders

Person leading warm-up	**% of respondents**	**Person leading warm-up**	**% of respondents**
Coach	13.0	On own	7.4
Captain	30.0	Varies	20.5
A person with exercise experience	28.4	No warm-up	0.6

The trend in these results demonstrate that any fitness information that was provided by the coach was in the form of advice regarding stretching, flexibility, strength, and conditioning. However, coaches largely opted not to give fitness advice (46%). Moreover, in general, players were not offered advice on fitness from anyone (43%); any advice that was sought was provided by a physiotherapist who played at the club (18%) or an individual with exercise knowledge (10%).

3.4.14 Results summary

The trend of the results in this study appear to show hockey players sustain non-contact injuries, particularly to the knees and hamstrings. There are few statistically significant differences in rates between genders, ages, performance levels and playing positions. The mechanisms of injury are largely changing direction, acceleration and landing, which cause muscle and ligament damage. These injuries occur primarily during the first half of the season, in training or in the first or second quarters of a game. Most of the injuries are minor with some lost playing time, usually less than one month. The respondents appeared to be experienced hockey players who trained outside hockey and undertook conditioning routines during their hockey sessions; however, few respondents reported injury prevention exercises and minimal advice was given by coaches or other players. These results indicate the trend as there were few statistically significant differences.

3.5 Discussion

3.5.1 Site of injury

The distribution of injuries that were reported in this study is similar to reported in previous studies (Murtaugh et al., 2001; Dick et al., 2007; Rishiraj et al., 2009; Sharma et al., 2012). Nearly all injuries that were reported in this study were to the lower body (87%), with just 13% to the upper body. Likewise, in the work conducted by Dick et al. (2007), most of the injuries were found to be to the lower body in both competition and training (40% game, 60% practice). However, in other studies, the numbers of injuries that were reported to the upper body increased as the performance level increased; two-thirds of all injuries were to the lower body for U21 elite female players (Rishiraj et al., 2009), whereas approximately half involved the lower body, in figures reported by Murtaugh (2001). However, in sub-elite male hockey, 47% of all injuries were reported to be to the lower extremity during competition, and a similar figure of 43% to the lower extremity was found within all male field hockey (Sharma et al., 2012). The lower-upper body distribution was 40%-60% in elite hockey in competition only. This may be due to the context, as players may perform at a higher intensity in competition and the ability to raise the ball high in the air, which would increase the number of injuries to the upper body. Another factor is likely to be the level of conditioning, which may reduce the incidence of lower-body injuries. More recently, a study of professional players reported that 68% of injuries were to the lower body (Delfino et al., 2018) and another reported that over 60% of injuries were to the lower body in indoor and outdoor club hockey (Hollander et al., 2018). This pattern was also reported among male club hockey players (Rees et al., 2020) the results reported by Sharma et al. appear not to follow this trend. However, the numbers of non-contact injuries were not specified.

These results are similar to those that have been found in other team sports; in football, for example, 87% of injuries have been reported to be to the lower extremity, most commonly to thighs, ankles and knees (Hawkins et al., 2001) with 58% of these being non-contact. In men’s basketball, between 57.0% and 61.5% of all injuries occur to the lower body (Dick et al., 2007) and similar figures are evident for women’s basketball, in which 57.9% and 60.6% of injuries occur in practice and games, respectively (Agel et al., 2007). In handball, 58% of injuries are to the lower body (Bere et al., 2015) while 40% of all injuries are non-contact.

In other hockey studies, injuries to the lower back and ankle/foot have been shown to be more common than to other anatomical sites, at 14% each (Rishiraj et al., 2009), whereas in this study the figures were 6.3% and 8.9%, respectively. Knees and hamstrings were the most commonly injured sites in this study, whereas in the study by Rishiraj et al. (2009) they accounted for 13% compared with 10% for the quadriceps. Furthermore, in male hockey, the most common injuries were to the ankle (13.5%), knee (10%) and lower leg (8%) (Sharma et al., 2012). More recently, Hollander et al. (2018) indicated that 59% of all injuries were to the lower body; thigh (19%), knee (10%) and ankle injuries (10%) occurred most frequently. This was compared with elite hockey competition, in which fewer injuries (38%) involved the lower extremity and, of these, thigh and knee injuries (25%) were reported most frequently, followed by calf and ankle (14%). An important point is that a study by Barboza et al. (2019) found that 75% of all injuries that occurred in the control group were to the lower extremity.

Although there appears to be a general pattern, methodological differences other than level and context may account for some differences. All the studies that have been mentioned were prospective in nature; some were self-reported (Barboza et al. 2018; Rees et al., 2020; Rishiraj et al., 2009); others were coach-reported (Barboza et al., 2019) or physiotherapist-reported (Hollander et al., 2018). Hollander et al. (2018) recognised that exposure data was difficult to exactly quantify because of the allowance of continual substitutions and each team had varying levels of personnel to record data. In addition, Barboza et al. (2018) used a convenience and relatively small sample of five teams.

3.5.2 Frequency of injuries

The non-contact injury rate that was found in this study was 4.09 per 1000 hours overall, which is broken down as 3.47 for males and 4.73 for females (a non-significant difference). These results fall within the ranges found by Barboza et al. (2018) and Cornelissen et al. (2020). The results regarding time-loss injuries in this study were similar to those found by Hollander et al. (2018) and Rees et al. (2020). This study compared injury rates between genders for practice and games (indoor and outdoor). The injury rate in the study was higher than the non-contact injury rate that was recorded by Barboza et al. (2019), who reported injury rates of 1.95 per 1000 playing hours (intervention group) and 2.88 per 1000 playing hours (control group) in an intervention study. An injury rate similar to this (2.5 per 1000 player-hours for acute injuries) was found by Barboza et al. (2018) in training; this study also reported that acute injuries occurred during matches at a much higher rate (12.3 per 1000 player-hours). This study also showed a much-reduced non-contact injury rate compared with figures reported by Rishiraj et al. (2009), who studied sub-elite female players (U21 internationals) and found a non-contact injury rate of 41.5 per 1000 athlete-exposures and overall injury rates of up to 68 per 1000 athlete-exposures. The difference in units between the Rishiraj study and this study is important. Athlete-exposures are of undefined lengths of time. The considerable discrepancy in injury rates may be due to this unit difference and the similarly large difference in the definition of an injury, as Rishiraj et al. recorded all injuries that were sustained both on and off the playing surface and which required medical attention.

The injury rates that were found in the current study were also lower than those that were recorded by the NCAA as reported by Dick et al. (2007). Indeed, the Dick et al. study showed that the inherent risk of injury in field hockey was 15.0 injuries in competition and 21.2 injuries in training per 1000 athlete-exposures. In a further NCAA study, Hootman et al. (2007) reported practice injury rates of 3.7 per 1000 athlete-exposures and 7.9 injuries per 1000 athlete-exposures in competition; however, these figures included both contact and non-contact injuries and, like Rishiraj et al., these researchers used the athlete-exposures unit. The definition of an injury was also different; an injury was recorded if it occurred in an organised, intercollegiate practice or match, required medical attention, and resulted in at least one day of time loss. The inclusion of time-loss and non-time-loss can make a notable difference; Rees et al. (2020) reported 4.0 time-loss injuries per 1000 player hours and 9.4 non-time-loss injuries. Likewise, Cornelissen et al. (2020) in a systematic review reported an injury rate of 1.47 time-loss injuries and 11.32 non-time-loss injuries per 1000 athlete-exposures for youth players. The methodological differences, including units of measurement and definitions, in the studies discussed above make inter-study comparison difficult.

During the hockey matches in the 2004 Olympics, injury figures were even higher, at 47 per 1000 hours for men and 14 per 1000 hours for women. Of these, non-contact injuries accounted for 36% among men and 14% among women (Junge et al., 2006). This equates to an injury rate of 16.9 per 1000 hours for men and 1.8 per 1000 hours for women. The calculated injury rate for males was higher than that found in the present study, while the rate in females was lower; however, taken together, the overall rate was much higher than the 4.09 injuries/1000 playing hours that was found in this study. This discrepancy may be due to the difference in context, i.e. largely competitive conditions at the elite level compared with the largely recreational conditions that were the subject of this study.

Theilen et al. (2016) demonstrated that in elite-level matches, injury rates were high at 29.1 per 1000 match hours for females and 48.3 per 1000 match hours for men. All these injuries were recorded using the same units as this study; however, only acute injuries were recorded (therefore no chronic injuries) as the authors defined an injury as one that required a stoppage in play and the athlete being unable to continue. Furthermore, these authors recorded only injuries in competition, where there is typically a higher incidence compared to practice. In addition, in both studies, the mechanism of the injury was not stated clearly enough to evaluate the non-contact injury rate.

The results in this study were much closer to those of more recent studies. For instance, Hollander et al. (2018) reported an overall injury rate of 2.7 per 1000 hours in practice and 9.7 in matches, which equated to 3.7 per 1000 hours overall. These authors also identified that most injuries occurred without contact (58.3%), which resulted in an injury rate of approximately 2-2.5 per 1000 hours. Furthermore, the study reported similar injury rates for males and females, although there were minor differences between the genders depending on the location (indoor vs. outdoor hockey). Similar results were ascertained by Barboza et al. (2018), with injury rates of 2.9 in a control group and 2.0 per 1000 hours in an intervention group. Both studies surveyed a cross-section of hockey players who had played in both practice and competition rather than elite players and/or just in competition conditions; even training sessions were included in the studies that were conducted by Junge et al. (2006), Rishiraj et al. (2009) and Theilen et al. (2016).

It is difficult to compare the injury data that was provided by Murtaugh (2001), Finch et al. (2002), Rauh et al. (2007), Sharma et al. (2012), and Engebretsen et al. (2013). Murtaugh did not report any non-contact injuries and considered injuries per athlete-year to assess injury risk; Finch et al. focused on comparisons of data across sports rather than depth of information regarding hockey injuries; Raul et al. did not report the injury mechanisms and focused on comparisons of the risks across sports and injury recurrence; Sharma et al. reported more descriptive data so no rates of injury were included, and Engebretsen et al. calculated relative risk (RR) rather than the numbers of injuries per 1000 playing hours. Hence the achievement of any useful comparison is a challenge.

Across 15 sports that were mainly team sports, the injury rate was reported to be 13.8 in competition and 4.0 in practices (per 1000 athlete-exposures); of these, 17.7% and 36% in games and practices, respectively, were non-contact (Hootman et al., 2007). These figures equated to a non-contact injury rate of 2.4 and 1.4 per 1000 athlete-exposures (approx.) in games and practice, respectively. These figures were similar to those reported for men’s and women’s basketball (Hootman et al., 2007; Agel et al., 2007; Dick et al., 2007). Non-contact injuries were reported to be the mechanism by which most injuries occurred in lacrosse, at a rate of 3.66 athlete-exposures in competition and 1.6 athlete-exposures in training (Dick et al., 2007). Even taking the units into consideration, these results are likely to be lower than the figures reported in this study.

Handball, however, appears to have a significantly higher non-contact injury rate as Bere et al. (2015) reported injury rates of 104.5 per 1000 match-playing hours and 15.9% of these were non-contact. The authors calculated that these figures equated to a non-contact injury rate of 16.6 injuries per 1000 athlete-exposures. This high figure may be due to the explosive nature of the sport, the frequent occurrence of the sidestepping manoeuvre and being played on a hard surface. The elevated injury rates may also be a result of prospective data collection from an elite level tournament.

In this study, noncontact knee injuries occurred most frequently for both genders – although the rate among females was higher (but non-significant) than that among males (1.06 per 1000 hours vs. 0.88 per 1000 hrs respectively) and within the knee-injury group, ligament injuries occurred at a rate of 0.34 per 1000 hours. Ligament injuries (which included knee and ankle injuries) in field hockey were reported to occur at a rate of 0.46 per 1000 athlete-exposures (Dick et al., 2007; Hootman et al., 2007). The latter study included ligament injuries in two joints and all contexts and therefore it was likely, units withstanding, to produce a lower rate than the present research. In other hockey studies, knee injury rates have been specified as 4.6 per 1000 athlete-exposures (Finch et al., 2002), 9.2 per 1000 athlete-exposures (Rishiraj et al., 2009), 10.3 (men) and 0 (women) per 1000 player matches (Junge et al., 2006), and 0.36 (approx.) per 1000 hours (Hollander et al., 2018). Consequently, the results of this study were similar to those of Hollander et al. in which the units were similar; however, the Hollander et al. study included contact and non-contact scenarios. Although other studies have reported higher rates of injury, these are exacerbated by the different units of measurement, the performance level of play and the context (i.e. matches only).

Other team sports of a similar nature to hockey also appear to show similar rates of noncontact knee and ligament injuries as were found in this study. Therefore, the risk of injury for hockey players appears to be similar to other similar sports. Agel et al. (2005) during a 13-year period reported that the anterior cruciate ligament (ACL) in female footballers was 0.33 per 1000 playing hours, which compared with 0.29 per 1000 hours in basketball. Moreover, in Australian rules football, knee injury rates were reported to be around 0.77 per 1000 hours overall; among these, knee ligament injuries occurred at a rate of 0.8 per 1000 hours (Orchard and Seward, 2002). Knee injuries (all) in lacrosse were found to be 1.65 (competition) and 0.48 (training) per 1000 athlete-exposures (Kerr et al., 2017), while rates of ACL injury in handball among females were reported to be 0.82 per 1000 playing hours for women and 0.31 per 1000 hours for men (Englund et al*.,* 2006). All these studies combined both contact and non-contact knee injury data; therefore, if non-contact injuries were to be extracted, the results would possibly align with those of the present study.

Hamstring injury rates in this study were reported to occur at a rate of 0.9 per 1000 hours. Most previous epidemiological studies of hockey injuries have not reported hamstring injuries specifically. Some have reported thigh injuries (Finch et al., 2002;

Hollander et al., 2018; Junge et al., 2006), upper leg injuries (Dick et al., 2007), and quadriceps injuries only with no hamstrings (Rishiraj et al., 2009). Rees et al. (2020) reported that 18% of all injuries were to the hamstring. Dalton et al. (2015) reported hamstring injury rates of 2.95 per 1000 athlete-exposures in field hockey (1.11 in competition, 3.54 per 1000 athlete exposures in training). The majority of these injuries occurred during running or general play and were non-contact in nature (Dalton et al., 2015). The studies of netball (Hopper et al., 1995; Langeveld et al., 2012) and lacrosse (Kerr et al., 2017) contained a dearth of information regarding hamstring injuries. Consequently, there is very limited information regarding this body part for comparison and as a result, the injury rates in this study are compared with those that have been reported for other team sports of a similar nature.

The results of this study regarding hamstring injuries were similar to those reported for professional football by Ekstrand et al. (2011b) of 0.93 per 1000 hours. Slightly higher rates of hamstring muscle strain have been reported in other football studies (for example, 3 per 1000 hours in Whalan et al. (2018) and in rugby, in which the rate of hamstring injury in both contact and non-contact conditions has been approximated at 2.9 per 1000 hours (Brooks et al., 2006). In Australian rules football, they have been reported to occur at a rate of approximately 4 per 1000 hours, and these injuries include all contact and non-contact injuries (Orchard and Seward, 2002). The higher figure for Australian rules football may be due to increased hamstring use to decelerate the shank following rapid leg extension in actions such as kicking and high-speed running both re frequently occurring in Australian Rules football (Gabbe et al., 2006). The results in other studies may be higher as the actions involve moving the ball which is not the case in hockey.

Given the results outlined here, the injury rate for hamstrings in the present study appears to be similar to or lower than those that have been reported in other sports. However, in other sports, the injury rates include data from all contexts (games, training or both), all levels of play, and all mechanisms (contact and non-contact) and is difficult to make direct comparisons. However, methodological differences (for example, injury definition and study design) may also play a significant role in this difference among studies.

Ankle injuries that were reported in this study occurred at a rate of 0.4 per 1000 hours, and of these, ligament sprains constituted the majority. These results are very similar to those of Dick et al. (2007), who reported injury rates in hockey of 0.37 (practice) and 0.58 (competition) per 1000 athlete-exposures. Rates of 0.9 injuries per 1000 person-days were suggested by Beynnon et al. (2005).

These injury rates were slightly lower than those that were reported in lacrosse of 1.74 and 0.48 per 1000 hours in competition and practice, respectively (Kerr et al., 2017). Several studies have reported ankle injury rates in football: injuries to ligaments have been reported as 2.8 per 1000 hours in general football (Whalan et al., 2018); as high as 4.5 per 1000 hours in the elite game (Andersen et al., 2000); and general ankle injuries of 0.4 per 1000 hours in training and 1.6 per 1000 hours for matches (Hägglund et al., 2006). In Australian rules football, ankle injuries were reported to occur at a rate of 2.7 per 1000 hours (Orchard and Seward, 2002).

In men's basketball, injuries occurred at rates of 1.06 and 2.33 per 1000 athlete-exposures in training and games, respectively (for all types of injury), while in women's basketball the injury rates were 2.6 per 1000 games/drills (athlete-exposures) with significantly more injuries in games than drills (Da Silva et al., 2007). Overall ankle injury rates in basketball were reported to be 0.95 and 1.89 per 1000 athlete-exposures in practice and games respectively (Agel et al., 2007). The surface and actions may influence the results in this sport.

The overall frequency of noncontact injuries in this study is similar to the rate reported in other hockey studies with non-elite participants however, lower than hockey studies with participants higher on the performance spectrum. The rate of noncontact knee injuries in this study is slightly lower than other hockey studies and that of other team sports. This pattern was also true of hamstring injuries. Ankle injuries in this study are comparable to other hockey studies however lower than other sports particularly those involving landing and played on hard surfaces. This study provides more explicit detail on noncontact injury rates and also provides rates for individual anatomical sites (especially hamstrings) compared to other hockey studies.

3.5.4 Mechanism of injury

The majority of injuries that were reported by participants in this study were sustained during changes of direction (or 'cutting'), landing and acceleration. Unfortunately, the level of detail that is contained in injury studies on the mechanism of injury within hockey is limited and this makes comparison difficult. For instance, in the studies by Murtaugh (2001), Junge et al. (2006), Dick et al. (2007), Sharma et al. (2012), Barboza et al. (2018), Hollander et al. (2018) and Rees et al. (2020), mechanisms of injury were allotted to general categories such as stick or player contact, while Theilen et al. (2016) specifically commented that the injuries were not linked to specific mechanisms. There is more detailed evidence in a study of Indian male hockey, in which injuries were reported to occur during tackling (44%), other (33%), dribbling (20%) and end furring (3%) (Sharma et al., 2012), although these were not specifically non-contact in nature. In other team sports, the dominant injury mechanism also appears to be a noncontact sidecut. Walden et al. (2015) report that nearly two-thirds of ACL injuries were noncontact and most of those were during a sidestep. This pattern is repeated in basketball (Krosshug et al., 2015) and handball (Olsen et al., 2005).

The low frequency of reports of non-contact injuries in sports other than hockey and the lack of detail limit the ability to compare the data of this study. Many of the categories are limited to descriptions such as contact with equipment such as a stick or with another player, violation of the rules, and other similar factors (Bere et al., 2015; Kerr et al., 2018).

The mechanism by which non-contact injuries are occurring in handball shows a similar pattern to that reported in this study. Studies of handball indicate that the plant and cut manoeuvre frequently cause injuries (Bere et al., 2015; Myklebust et al., 1998). In basketball, the mechanism of injury typically originates from general play (36.02%), landing (20.34%) and warming up (14.83%) (Bigoni, cited in Volpi, 2016).

Despite the lack of data, there appear to be patterns of injury mechanism per anatomical site. Further to the information above, in basketball, the mechanism for knee injuries (including ligament injuries) has been reported to occur during landing (58.9%) and cutting (10.3%) (Krosshaug et al., 2007). These mechanisms are also of concern to handball players, as exercises to improve the technique of these actions have been implemented (Olsen et al., 2005). Indeed, the mechanisms that are described for other sports are markedly similar to those found in this study.

The mechanisms of hamstring injury that were found in this study were acceleration, slipping and cutting, i.e. actions that involve considerable eccentric muscle contractions. Hamstring injuries often occur during running, specifically sprinting (60-80% of hamstring injuries), and kicking (Liu et al, 2012). Similar figures for running in rugby (68%) have been provided by Brooks et al. (2006). Both injury mechanisms involve phases of considerable eccentric contraction of the hamstring, which occurs in the late swing phase of the gait cycle when the lower leg is decelerated before a foot strike (Buckthorpe et al., 2018). Both actions occur frequently in these sports, hence the elevated injury rates.

Ankle injuries that were reported in this study were found to occur during acceleration, sidecutting and slipping. All these actions involve landing. This pattern of ankle injuries is similar to those that have been reported in basketball, in which these injuries occur during cutting, turning and pushing off (Bigoni, 2016 cited in Volpi, 2016); half of these ankle injuries were reported to take place during landing (50% non-contact) and sharp twisting/turning (30%). This may be in part due to the playing surface.

Those sports that have a more frequent and forceful landing, especially in multiple planes, appear to have higher incidences of ankle injuries. For example, during a five-year netball study, it was found that the ankle and especially the associated ligaments were the most frequently injured anatomical sites (47.4% of all injuries) which may be due to the considerable number of landings on a hard surface that occur in this sport. This figure included 20% of all injuries to ankle ligaments and was much higher than the figures reported in the present study. This is because the netball study included contact and non-contact injuries and because of the nature of the sport. Also, it is also important to factor in other considerations such as age and other life commitments. However, the mechanisms of injury that were discussed were similar to those considered in this study as they included landing (24.5%) and slipping (13.8%) (Hopper et al., 1995). In a recent study into netball injuries, the ankle was still the most frequently injured anatomical site

(35.6%) (Best, 2017). These injuries may also be age-related, therefore, this may have implications for any intervention such as the intensity (Nigg and Herzog, 2007).

Nonetheless, there is limited detail in epidemiological studies that have been conducted in hockey and other team sports regarding the mechanism of injury for each anatomical site. While it is possible to infer mechanisms from reports of other sports, this study provides a valuable addition to the literature.

The types of injuries that were sustained by participants in this study were approximately 50% new/index and 50% recurrent. A markedly different ratio was reported by Rishiraj et al. (2009). Their study found that 77% of injuries were recurrent, however, there may be variations in definition that account for some of this difference. The type of injury was not reported by most authors (Dick et al., 2007; Engebretsen et al., 2013; Finch et al., 2002; Furlong and Rolle, 2016; Hollander et al., 2018; Junge et al., 2006; Murtaugh, 2001; Theilen et al., 2016). In other sports, there is the opposite trend; for instance, in a review of netball injuries, 72.2% were reported to be new (Langeveld et al., 2012).

3.5.5 Characteristics of injured players - Age

In this study, there was a gradual but not statistically significant increase in injury rate with age. There is little discussion within the hockey literature regarding injury rates and age. This could be due to the limited populations that have been investigated; for example, Rishiraj et al. (2009) considered U21 internationals, Furlong and Rolle (2016) studied U18 players, and Hollander et al. (2018) studied players at a competition level below the included group. It is also likely that players stop taking part as their ages increase, either because of injury or fear of injury and hence there are few older players who are available for study.

However, there is mixed evidence of a relationship between age and injury rate. Arnason et al. (2004) highlighted the occurrence of a significant increase in the numbers of hamstring injuries with age with football players, whereas Hägglund et al. (2006) did not show a similar trend. In a review of the risk factors for lower extremity injuries, Murphy et al. (2003) found mixed evidence that risk increased as age increased. Across 35 sports, it was found that the mean age of participants was 21.7 years and that 15-19-year-olds sustained the most injuries (Åman et al., 2015). Furthermore, Stevenson et al. (2000) demonstrated that, across several team sports, the injury rate increased to approximately 20 per 1000 hours for 26-30-year-olds, yet it decreased for the 31-35, 36-40 and 41+ age groups; consequently, there was no positive correlation between age and injury.

3.5.6 Playing position

The results of this study show injury rates of 2.5/1000playing hours for goalkeepers, 3.57 for midfielders and defenders and 5.8 for attackers. They indicated that there was a non-significant difference in injury rates between playing positions but there was a trend, which suggested that defenders and midfielders sustained injuries at the same rate and attackers suffered a slightly higher injury rate. This may be because these players spend more time in critical areas, such as near the goal. However, these results may be influenced by the number of respondents in each position.

The trend that was identified in this study was similar to two other studies. Rishiraj et al. (2009) showed that backs and forwards accounted for 32% and 36% of injuries, respectively, whereas midfielders sustained 22% of injuries and goalkeepers sustained just 10%. A similar pattern was observed by Rees et al. (2020). However, there were contrasting results reported by Murtaugh (2001), who found that goalkeepers had the highest injury rate followed by midfielders, while defenders and attackers experienced similar injury rates. Those who played in multiple positions showed the highest injury rate of 0.51 injuries per athlete year. Attackers and defenders may have similar injury rates appears to be a trend maybe because of the mirroring of movements and similar areas on the pitch. Some studies (Murtaugh, 2001; Rees et al., 2020) had a relatively small number of goalkeepers as participants, however, it is proportionate to the number of within a hockey team.

In Indian male hockey, the injury frequency appeared to be similar for midfielders and defenders (6-7% of all injuries for these positions), whereas forwards (8.73% of all injuries) were slightly more susceptible (Sharma et al., 2012). This Indian study produced interesting figures for goalkeepers, who experienced approximately 4% of injuries, while non-contact injuries were reported to show similar frequencies across all positions (6% for midfielders, 5.5% for forwards and 7% for defenders) (Sharma et al., 2012). These results were mirrored in a more recent study by Hollander et al. (2018), which highlighted an even spread of injuries across the outfield positions. Barboza et al. (2018) also found that a small percentage of injuries were sustained by goalkeepers (5%), while over half (53%) of all injuries were sustained by midfield players.

All the studies above included data for all injuries, which may have accounted for the higher rates of injury that were reported by Murtaugh (2001), as goalkeepers were likely to sustain more contact injuries (contact with other players, the ground and the goal). Further, each player may play more than one position and/or perform actions that are similar to those performed in other positions. However, if positional differences can be established, this has implications for the content of any intervention.

3.5.7 Level of play

This study identified no significant differences between skill levels and injury rates and no trend between levels and injury rates. Although there was a notable increase in the injury rate in the Masters category, this may have been due to the age of the participants rather than the performance level. These results are similar to those that have been reported in the NCAA, in which the lower divisions exhibit similar injury rates to those of the higher ones (Div. 3 = 7.25, Div. 2 = 10.62, and Div. 1 = 8.19 injuries per 1000 athlete-exposures).

In contrast, Sharma et al. (2012) demonstrated that, as performance level increased, the injury rate decreased: district players were reported to sustain 31% of all injuries, state-level players sustained 25.2% of all injuries, and national players sustained 23% of injuries (university players sustained 19.4%). The evidence for this parameter from other studies, as in the case of the issues that surround age, is limited since each study was focused on a particular population; also the recording procedures that were used (for example, data collection methods, prospective and retrospective research design, units of measurement and injury definitions) were slightly different. This pattern needs further investigation, as, for one injury, Harmon and Dick (1998) and Harmon and Ireland (2000) report no difference in ACL injury rates in the divisions within the NCAA.

With regard to other similar team sports, a review by Murphy et al. (2003) reported mixed evidence to indicate a global trend in which netball showed greater injury rates (for lower extremity and back injuries) as skill level increased as there was a greater injury rate for college than for high-school basketball players. This pattern has been reported by Hopper et al. (1995) in netball, Hoskins and Pollard (2003) in Australian Rules football and by Soligard et al. (2010) for football (soccer) players. In contrast, American football players and Czech football players (Chomiak et al., 2000) showed the opposite trend. Therefore, any generalisations regarding the level at which players perform and injury rates should be limited and needs further investigation.

3.5.8 Timing of injury - training or competition

Injuries that were reported in the present study were sustained more frequently during competition (62.2% of all non-contact injuries) than in training (37.2%). This appears to fit with findings from other studies, particularly that of Rees et al. (2020), who reported that 59.5% of all injuries were incurred in matches and 40.5% in training. Hootman et al. (2007) reported practice injury rates of 3.7 per 1000 athlete-exposures and injury rates in competition of 7.9 per 1000 athlete-exposures.

At the elite level, across several sports, injuries were found to occur more often in competition (55%) compared with training (45%) (Engebretsen et al., 2013). In team sports, this difference increased: 75% of all injuries were sustained during competition and 25% in training. Regarding time-loss injuries, 81% occurred in competition (Engebretsen et al., 2013), while in the study conducted by Theilen et al. (2016), 66.6% of all injuries were sustained in competition. However, in this case, this might be because the focus of the study was injury prevalence during competition conditions and consequently the duration and intensity of training time would be considerably reduced.

Further variation was reported by the Hollander et al. (2018) study, in which 61% of injuries were reported to occur during training and 39% in competition. This study focused on all hockey injuries and it may have involved more training and a greater intensity of training compared with the study that was conducted by Theilen et al. (2016).

3.5.9 Injury trends during a game

In this study, there was a trend (not statistically significant) for more injuries were reported to have occurred in the third quarter of a game (minutes 35-52) followed by the second and first quarters (Figure 3.4). The third quarter is just after half-time and therefore follows a rest period, during which muscle temperatures are likely to decrease by 2°C (Lovell et al., 2007) and this occurrence is likely to lead to an associated performance decrease (Mohr et al., 2003). However, the distribution of injuries between the two halves was relatively even.

The pattern in this study was not replicated in previous studies. Rishiraj et al. (2009) who studied injuries in sub-elite female hockey players also reported a considerable difference in the injury rates in each half (first half = 27.7, second half = 107.3 per 1000 athlete-exposures) with a similar pattern in training (first half = 27.7 and second half = 107.3 per 1000 athlete-exposures). This trend may be a consequence of fatigue. A different pattern was evident in elite hockey, there was a much more even proportion of injuries in each quarter with a slight increase in the first quarter, with the highest level in the fourth quarter (Theilen et al., 2016). The athletes at the elite level may have a greater level of conditioning than those studied by Rishiraj et al. (2009), although fatigue may still be a factor in the fourth quarter. Other epidemiological hockey studies have not reported these data, and more generally this parameter has not been reported frequently.

In terms of related team sports, there are varying trends. In football, for instance, the number of injuries has been shown to rise throughout the first half, to be followed by a reduction at the beginning of the second half, with a peak at 61-75 minutes and then another drop (Ekstrand et al., 2009; 2011a). Similarly, injuries in rugby are more likely in the second half, with more injuries incurred as the game progresses (Roberts et al., 2013). This shows a trend towards an increase in injury rate with fatigue. In handball, on the other hand, the injury rate increases towards the middle of each half rather than towards the end of each half (Langevoort et al., 2007). This may be due to an increase in intensity; the authors provide no explanation. It may be possible to somewhat mitigate against fatigue-related injuries in hockey as unlimited continuous substitutions are permitted, also, at the elite level, the playing time has been slightly shortened and there are additional breaks that may also reduce these injuries.

Some studies have shown that performance decreases after the traditional half-time rest (Mohr et al., 2005), whereas a half-time re-warm-up attenuates these decreases (Edholm et al., 2014). Furthermore, a sedentary half-time period can reduce eccentric hamstring strength and increase the chances of a non-contact hamstring injury (Edholm et al., 2014). This has led to the occurrence of more injuries during the first 15 minutes of the second half in football, and these injuries typically occur during actions that involve deceleration (Russell et al., 2015). In addition, Bixler and Jones (1992) (cited in Fradkin et al., 2006), found that sprains and strains were significantly reduced if a three-minute re-warm-up was instituted before the start of the second half. Small et al. (2009) found that a half-time multidirectional, intermittent exercise programme improved stabilisation after single leg hops in both the vertical and medial-lateral planes, which suggested that there was an injury prevention as well as a performance benefit to the participation in a re-warm-up during the half-time interval.

The evidence provided in this study and supported by others suggested that injuries occur more often in competition than training, although equivocal. In competition, there were slightly more injuries in the 3rd and 2nd quarter of a match reported in this study. The trend for more injuries after half time appears to occur in other sports so a half-time re-warm up may be advised. However, these patterns need further investigation.

3.5.10 Injury rates throughout the season

This study found that there was a trend (not statistically significant) for more injuries in the first half of the season, especially in September, October and November, than in the equivalent period of the second half of the hockey season (i.e. February, March and April). There was also an increase in the number of injuries that were contracted during the in-season, with a slightly lower rate in the pre- and post-season. The increase in injuries at the start of the season may be due to either the increase in the conditioning often observed or a sedentary period (off-season) or a combination of both.

The pattern in this study was similar to that found in rugby (Roberts et al., 2013). In non-elite team sports, Stevenson et al. (2000) and Finch et al. (2002) both reported a spike in injury rates during the first month after the post-season. This trend may occur because those susceptible to injury are vulnerable after a period of time out from the sport in the off-season. The injury rates in elite-level football, however, are much more consistent throughout the year; the rate ranges between 5 and 6 per 1000 hours for trauma injuries and just over 2 per 1000 hours for overuse injuries for most of the season, with a drop in rates outside the competition period (Ekstrand et al., 2011a). This consistent injury-rate pattern has been identified in a number of sports within the NCAA (Hootman et al., 2007). Therefore, an approach adopted by Weir et al. (2019) may be part of the solution. The approach in that study was an intensive injury prevention programme (4 x per week) to mitigate against the trend found in this study and supported by others.

3.5.11 Nature of injuries – type of injury

The most common injury that was reported by participants in this study was muscle damage (42.4%), followed by others (13.3%) and then ligament damage and bruising. As a comparison, Rishiraj et al. (2009) reported that strains (40%), tendonitis (24%) and contusions (17%) were the most frequent types of injury, while other injuries including ligament damage accounted for less than 5%. Earlier research by Murtaugh (2001) reported that ligament injuries accounted for 40% of all injuries. The next most common were contusions followed by fractures (15% each), and muscle strains accounted for less than 10%. In male hockey, contusions have been shown to account for nearly 30% of all injuries followed by sprains (13.5%), tendinopathy (12%), and those that cause a haematoma (swelling of clotted blood) (11%) (Sharma et al., 2012).

In a more recent study by Hollander et al. (2018), muscle strains and contusions were the most frequent types of injury that were reported in both indoor and outdoor hockey and in both genders. These data are similar to those of Rees et al. (2020), who also reported muscle strains, pain, contusions and ligament sprains as the most common injuries.

Contact injuries are more likely to result in bruising due to contact with the player, stick or ball (these injuries account for 40% of all injuries, according to Sharma et al. (2012), especially when there is damage to the upper body and fractures (especially of the fingers)). In contrast, non-contact injuries are more likely to result in muscle or ligament damage. This was found by Barboza et al. (2018), who reported that acute injuries, caused by no contact, and strains occurred to the hip or groin muscles and hamstrings (10% each) and some caused sprained ankles, lower back pain and lower leg haematomas (6% each).

Injuries in hockey appear to be more acute than chronic in nature. More than half of the injuries that were specified in this study were acute, and they affected most often the ligaments and muscles across all parts of the lower extremity. This finding appears to be similar to those of other studies; Hollander et al. (2018) and Barboza et al. (2018) reported more acute injuries (62.5% in the control group and 70.5% in the intervention group) than chronic instances, although the data were constructed differently in each of the studies and this prevents a straightforward comparison.

An alternative representation of the data that were collected in this study shows that new injuries (index) caused 21.9 days of time-loss vs. 11.7 days of time-loss for recurrent injuries. These figures are larger than those identified by Delfino et al. (2018) (these researchers reported time-loss of between 3.9 and 5.7 days for acute injuries and 1.8-2.1 days for overuse injuries). Other team-sport data show a mixed picture. Rugby players in academies had fewer days of time-loss for index injuries (18) vs. recurrent injuries (12), whereas school-based rugby players experienced more days of time-loss (60) for recurrent injuries compared with new injuries (Palmer-Green et al., 2015). This parameter has received little attention in the epidemiological literature regarding hockey, and as a consequence, further investigation is required.

3.5.12 Injury severity

According to the data that were collected in the present study, 31.4% of all injuries did not result in time-loss; 17.4% caused players to miss the next session or game; 19.8% caused two to four weeks to be missed, and 10.4% caused either a week or one to two months of hockey to be missed. This means that nearly two-thirds of the players who answered the questionnaire sustained a slight or minimal injury, nearly 7% sustained a moderate injury, 15% a mild injury, and approaching 10% developed a severe injury. These severities are reduced compared with the figures that were obtained from other studies, with the most recent study reporting significantly higher levels: in this case, 38% of injuries were mild, 30.5% were moderate, and 31.5% were severe injuries (Hollander et al., 2018). The mean time-loss was reported to be lower in elite players (0.5 days lost) than in players of lower levels; however, the median time-loss was 28 days for all injuries (Delfino et al., 2018). The Barboza study also showed that time-loss for acute injuries was greater (median = 34.8 days, mean = 1 day) than for overuse injuries (median = 21 days, mean = 0.0 days). These results are similar to those in this study (median = missed 2-4 weeks, a 'moderate' injury). In recreational men's hockey, severity was found to be slightly less than that reported for elite hockey and ranged from five days of time-loss for contusions, seven to nine days of time-loss for knee injuries, hip/groin and hamstring injuries and up to 35 days of lost time for elbow fractures (Rees et al., 2020). However, these studies included all injuries rather than just non-contact, which may have contributed to the difference.

Barboza et al. (2019) extrapolated the data for non-contact injuries and specified that the control group showed an average time-loss of 5.3 days compared with 6.2 days in the intervention group. The time-loss results of the study under investigation were higher in comparison with those of Barboza et al. (2019), and this could be due to the population (i.e. the whole population as opposed to just those involved in the investigation). In addition, this study covered the whole season rather than just the period of the investigation. Rishiraj et al. (2009) stated that most players (81%) were reported to return to play within seven days (therefore sustaining 'mild' injuries or less) and a further 17% returned within eight to 12 days (designated as either 'mild' or 'moderate' injuries). In elite competitive hockey, injuries have been shown to result in approximately 0.23 time-loss injuries per 1000 hours, and women's hockey results in four times more injuries than men's; however, this is primarily due to the high number of head injuries among females and the reduced level of lower-extremity injuries in elite competition (Junge et al., 2006).

In this study, there were a few long-term injuries (hip injuries) that may have inflated the time-loss figures found. Also, this study used a retrospective recall research design, which contains an inherent level of report/recall bias, especially as some injuries may have occurred at the start of the previous season. In contrast, a prospective research design may provide a more accurate account of the injuries and their characteristics.

3.5.13 Combined results regarding injury location, injury rate, mechanism, type of injury, timing, and severity

The combination of epidemiological data in this format enables a more comprehensive understanding of the injuries that were sustained by league hockey players in Scotland. The data in this study indicates some trends as many of the comparisons were non-significant. Some of the data of this study is provided in Table 3.11. As the table shows, knee injuries were the most frequent (0.88 per 1000 hours) and were caused predominantly by a sidecut or landing, which typically damaged ligaments and muscles. These incidents usually occurred in competition and resulted in two to four weeks of time loss.

This data format contrasts with the more descriptive data that have been provided in many previous epidemiological studies, such as those produced by Murtaugh (2001), Rishiraj et al. (2009) and Sharma et al. (2012). Comprehension of the aetiology (step 2 of the van Mechelen et al. (1992) model) is particularly pertinent for the provision of preventative recommendations or the implementation of interventions. Such analysis has been largely provided by Dick et al. (2007), Hollander et al. (2018), and partly by Theilen et al. (2016).

The analysis demonstrates several similarities between the results of this study and the data that were provided by the NCAA (Dick et al., 2007). Non-contact injuries that caused ligament damage was prevalent in both this study and the NCAA results and led to lost playing time of between 18 and 23 days during both competitions and training. It is important to remember, however, that the NCAA study reported injuries that led to the loss of ten or more days of playing time.

Both this section and section 3.5.8 above, which discusses the severity of injuries, contain various definitions of severity, as do other studies. For example, in this study the definitions were taken from Fuller et al. (2006), whereas in the study of the NCAA data, Dick et al. (2007) used ten days as the cut-off for severe injuries; Murtaugh (2001) did not define severe injuries at all, and others such as Barboza et al. (2019) reported injuries in terms of time-loss per 1000 hours only.

3.5.14 Coach practice and advice

The data that were collected in this study suggest that few players altered their playing style to avoid pain or injury (Table 3.12). Therefore, the injury data is likely to be representative of normal play situations, given that players did not protect themselves by playing with a reduced intensity or by avoiding actions that could have resulted in injury. This may affect the participation rates in both the short and long term. It also appears that among the respondents, there was little fitness activity outside hockey training sessions. The activities that did take place primarily consisted of cardiovascular training and stretching with some balance, stability and weight training. These sessions occurred twice a week. Therefore, the study participants took part in a few injury prevention activities or hockey-specific conditioning programmes to reduce injury rates. These types of exercises have been shown to reduce injuries (see 2.7.6 and 2.8.4-6).

The respondents reported that in general, the captain led the warm-up rather than the coach. Indeed, the evidence from this study showed that the coach led the warm-up only 12.8% of the time. Instead, the activity frequently was led by players who had exercise experience, or by others. Nearly 8% of players warmed up on their own. This evidence suggests that coaches have little involvement in or influence over the warm-up procedure. This may affect the quality (time, intensity, and concentration) of the warm-up and consequently influence injury rates.

The players also reported that coaches rarely offered advice on injury reduction (62.6% of coaches did not provide any advice on injury prevention), although some gave advice regarding flexibility, strength and conditioning, or balance and stability. These results are similar to those reported by Gouttebarge and Zuidema (2018), which indicated that 61% of hockey coaches did not advise their players on methods of injury prevention.

This may have been because their knowledge required improvement (as self-reported by 55% of respondents in this 2018 study) or because they believed that it was the responsibility of the players (88%) to collect their own information. In contrast, more than half (56%) of the players appeared to believe it was the responsibility of the coaches and many would have liked to have been better informed so that they could play a more proactive role in injury prevention.

There is good evidence that coaches can influence participant safety (Stevenson et al., 2000) and that they can create a culture of injury avoidance within sport (Pensgaard and Roberts, 2002). Indeed, Stevenson et al. (2000) found that, when participants took part in a programme that was designed by a sports professional, the risk of injury was reduced by 32%. Although the amount of safety advice that is given by coaches varies, it also appears that coaches are receptive to improvements in the implementation of programmes in injury prevention. Accordingly, White et al. (2014) demonstrated that more than 94% of netball coaches showed positive attitudes towards correcting landing technique following education; the authors also concluded that the presence of strong coach role models would assist in the promotion of injury prevention practice. Furthermore, it is evident that, after coaches have been given injury prevention education, almost all coaches use that knowledge in practice and pass it on to the players. As an example, in a study by Gianotti et al. (2010), 89% of coaches changed their approaches after attendance at an injury prevention course for netball. Ultimately, these authors suggested that, although more research was required, coaches' education about injury prevention could be an effective strategy to reduce injury rates.

Nonetheless, as explained by Gilbert and Trudell (2004), most coaches see their role as helping their teams to win and the achievement of this may take their attention away from the warming up/injury-prevention process. This focus on winning, coupled with the coaches' opinion that it is the players' responsibility to warm up, means that little attention has been paid to a hugely important influence of coaching can have on injury prevention.

Coaches are often educated through the sports-coach education structure that is set up within each sport and country. It can also come through playing experience, a mentoring system, or discussions with foreign coaches (Lemyre et al., 2007). Notably, coaches rarely interact with rival coaches or peers; they like to interact with coaches who are involved in the game at a lower level or with foreign coaches, yet Lemyre et al. (2007) and Malate and Feltz (2000) found that coaches preferred formal coach education. This should be noted by developers of coach education.

3.6 Strengths and limitations

The aim of this study was to investigate noncontact injuries in hockey using an online cross-sectional survey. A strength of this study was that the questionnaire used was tested for validity and reliability. Furthermore, the questionnaire was designed specifically designed to assess noncontact injuries.

The questionnaire was completed retrospectively which was a limitation of this study. Prospective monitoring of injuries and exposure can record this data with greater accuracy. This research design does involve considerable commitment from physical trainers, physiotherapists or coaches which not always be available also may limit the quantity of data. However, the involvement of these professionals may reduce the misinterpretation of epidemiology (for example the mechanisms and nature of injuries) as bruising was 3rd most common injury and reduce the frequency of the selection of 'other'. This injury maybe more often associated with contact injuries, in this context, contact from the ball.

An advantage of the online, retrospective approach there was the opportunity for a greater number of respondents albeit with reduced efficacy. Interestingly, found that both approaches produced proportionally similar results (Junge and Dvorak, 2000). This study had a response rate of nearly 5% of the population, a low response rate but not unexpected. Therefore, a larger sample size (between 15-20% of population, Baruch and Holtom (2008)) would be desirable and give the data greater efficacy.

The structure of the questions in this study were used as they were deemed relevant, comprehensible, however, they were closed questions which may limit the responses. Also, the inclusion of 'other' was deemed both relevant and comprehensible in the development process however, this option was frequently used so omitting this option should be given in future research and other options could be in it's place. The use of open questions could be considered in future studies.

3.7 Study 1 Conclusions

This is the first study that explored the epidemiology of hockey non-contact injuries in Scotland. There was a trend for non-contact injuries to occur more frequently among females, older players and those who play in attacking positions. They affect mostly the lower extremity knee, the hip and ankle joints and the musculature of the knee and hamstring. They are typically caused by a change in direction, sudden acceleration or landing, and the severity is predominantly slight, mild or moderate. They occur more often during training than in competition and during the first half of the season rather than in other periods of play. Although coaches report the use of strength and conditioning exercises in their training sessions, these rarely include injury prevention exercises. Further research employing prospective designs is required to explore the characteristics of the non-contact injuries in hockey. Moreover, to reduce noncontact injuries, an exercise-based injury prevention programme, similar to other interventions in hockey and sports other as well as using the recommendations in 2.7 and 2.8, could be implemented.

Chapter Four: Warm up Practice in Recreational Hockey (Study Two)

4.1 Introduction

Observation is a commonly used method in sport to explore new insights about supporter behaviour, coach behaviours and warm-up content (Avest, 2010). Specifically, in hockey, observation such as time and motion analysis has been used to determine the motions of the players (Spencer et al., 2004). The use of more accurate techniques, such as the global positioning system (GPS), has superseded this process during both training and matches (White & MacFarlane, 2013).

A recommended structure to a warm up is the 'RAMP' approach (Cone, 2007). The benefits of a warm up are described in 2.6. The 'raise' section involves exercises that increase the heart rate (HR), increases muscle temperature ready for the upcoming movements. The 'Activate' or activation is the section to contraction the muscles onset (Kang et al., 2020, p1). This can be exercises to target specific muscles. The 'Mobilise' section through dynamic flexibility aims to reduce muscle stiffness and increase range of motion (Gil, 2019) in the sport about to be performed (Jeffreys, 2007). The final part, the 'Potentiation' or post-activation potentiation is the transient increase in muscle contractile performance following previous 'conditioning' contractile activity (Sale, 2002 and McGowan 2015) via high intensity activity such as sprinting and jumping.

Currently, only Avest (2010) has conducted an observational study to investigate the warm-ups in sub-elite hockey (n = 13; eight of males, five of females) that were used in the National and Premier Leagues in England. This study involved overt use of the behaviour observation form (Appendix 4.2) and followed up with semi-structured interviews to ascertain the coaches' perspectives of the warm-ups. The results of this study showed that usually warm ups included 4 sections with a mean total duration of 35.66 minutes (±4.33 minutes). The mean duration of the 'raise' component of the warm-up was 2.66 minutes, of the 'activate and mobilise' was 12.03 minutes, and of the 'potentiate' section, 20.95 minutes. The interviews indicated that coaches were influenced in their warm-up planning by their playing experience, occupation and educational background. Most coaches would have preferred a longer duration of warm-up than was observed (38.1min approx.); however, there was no further information on how they wished to use this extra time. It was observed that 77% of the warm-ups contained static stretching exercises and 100% of them contained dynamic stretches.

The theory of the warm-up process has been well-documented (Bishop, 2003; Cone, 2007; Marek, 2005; Younge, 2007; Young and Behm, 2002). However, to the author's knowledge, there is limited research on the implementation of warm-ups in practice in different sports. Among the few studies that have investigated this area, one found that only 54% of golfers performed any kind of warm-up before performance, while just 3% performed an adequate warm-up and most just performed practice swings on the tee (Fradkin et al., 2001; Fradkin et al., 2003). Likewise, 60% of netballers did not perform a warm-up, and this was suggested to increase the injury risk by 48% (McManus et al., 2006). The approach to warm-ups in netball has changed little since Steele (1990) reported that only 47.5% of veteran players performed a warm-up. In professional football in both the Premier League and the Championship in the 2010/11 season, the average duration of the warm-up was 31 minutes and highly variable among teams (ranging between 15–45 min) (Towlson et al., 2013). Also, Towlson et al. (2013) investigated attitudes towards warm-ups; the most important elements of the warm-up were deemed to be increasing blood flow and muscle temperature. Elevation of baseline oxygen consumption decreased muscle and joint resistance, mental readiness and post-activation potentiation were deemed to be somewhat important. To a lesser extent, arousal and technical readiness were reported as important (Towlson et al., 2013). Interestingly, injury prevention was not seen as an important element of a warm-up.

The approach and attitudes of coaches and players towards warm-ups and NMT in hockey could be improved. The evidence chapter 3 of this thesis shows that only 13% of players report that their warm ups are delivered by their coaches while 7.4% of players warm up by themselves. Coaches also offer little injury prevention advice and limited injury prevention exercises or programmes are implemented in training. The benefit of an NMT-style warm up are described in 2.7.

In summary, there is limited evidence of the content of warm-ups in different sports and particularly in hockey. From what is known, a good amount of time is spent on each section of the warm-up but not as much as coaches would like. However, the only known research of warm-ups in hockey (Avest, 2010) was conducted in the sub-elite game and therefore further investigation is required at the recreational level. Also, Avest (2010) used a convenience sample therefore, there could be an improvement in ecological validity. Also, the internal reliability, for example an intra-observer reliability test, could be improved upon. Furthermore, the follow-up interview by Avest focused on the aim of the warm up from the coaches perspective whereas this investigation will have an injury prevention focus.

Therefore, the aims of this study are: 1) to investigate the warm-up practices that are employed in recreational Scottish hockey and to compare them with published warm-up recommendations; and 2) to explore the perceptions of hockey coaches regarding warm-ups.
The objectives of this study are:

1. To observe the current warm-up practice in recreational hockey in all regions Scotland.

2. To compare time spent in each element of the warm up.

3. To explore coaches' perceptions of the warm-up.

4.2 Method

4.2.1 Team participants

This study used an overt observational design that employed an observer instrument (Appendix 4.2). After ethical approval had been granted by the institutional ethics committee (Appendix 4.1), teams were randomly selected (using an online number generator) from each league in the Scottish Hockey league structure (in the 2015/16 season) Tables 4.1, 4.2 and 4.3 below) to avoid selection bias. Teams that comprised both genders were chosen and presented in Table 5.5.

Table 4. 1 Number of teams in each Scottish district in 2015/16*, **

	No. of teams in each district					
Gender	**North**	**Midlands**	**East**	**West**	**South/South West**	**Total**
Male	10	13	14	19	2/0	58
Female	14 (incl. islands)	11	18	26	2/1	72
Total	24	24	32	45	4/5	130

Table 4. 2 Numbers of teams in each league in 2015/16 (national and regional),**

	No. of teams					
Gender	**National league 1**	**National league 2**	**National league 3**	**Regional league 1**	**Regional league 2**	**Regional league north**
Male	10	12	8	10	12	4
Female	10	11	-	10	9	4
Total	20	23	8	20	21	8

Table 4. 3 Numbers of teams in each league in 2015/16 (district)*, **

	No. of teams			
Gender	**East**	**West**	**North**	**Midlands**
Male	37	38	9	10
Female	18	40	11	9
Total	55	78	20	19

*Several clubs have more than one team
**Sometimes one club has more than one team in the same league

The chosen teams were contacted by the researcher by telephone to seek initial permission to observe the teams while they performed warm-ups and for the coach to complete the post-warm-up questionnaire. Once permission had been granted, the managements of the contacted teams and researcher agreed dates and times when the researcher would observe the players and coaches before a training session or a match.

Before the observations took place, intra-observer reliability was assessed (see 4.2.2). Immediately prior to observation of each team, written permission to be observed and consent to take part in the study were obtained from both the players and the coach (Appendix 4.1). Observations were in real-time. There was no video capture as this was deemed unnecessary after the pilot work was completed. The coach was given the post-warm-up questionnaire for completion immediately after the warm-up (Appendix 4.3). The aim of the coach questionnaire was to gain a coach profile and to establish the aims of the warm-up, whether it was completed as intended, what, if anything, was missed out and what elements would be included in the future. The coach indicated when the warm-up had begun, the stopwatch (Sportline Inc., 240, China) was started and the observation began. The observation continued until the training session started (as indicated by the coach) or the match had begun. The warm-up observation was recorded by completion of the data observation sheet (Appendix 4.2). This sheet was adapted from the behaviour observation form that was developed and used by Avest (2010) to record actions (activity was recorded every 30 seconds) within the warm-up and to create a timeline for the warm-up. Actions that occurred frequently were assigned a code to aid the speed of recording (Appendix 4.5); others were recorded in the 'other' section or written out in full.

The actions were then assigned to the categories of either pulse raiser (usually all actions from the start of the warm-up that did not involve a hockey stick and ball and which included any mobilisation, activation and potentiation) or skill rehearsal (usually on-pitch hockey-skill movements that players practised).

Further analysis led to the division of the warm up into the RAMP sections that were explained in section 4.1 (Jeffreys, 2007).

The collected data were transferred later to a Microsoft Excel spreadsheet and subsequently to the SPSS software program for statistical analysis (SPSS®, IBM® SPSS®, 2015, v21). For each variable, means and 95% confidence intervals (CI) were provided.

After the warm-up, the coach completed the questionnaire which included a section on how the warm up was developed and performed (5 items), the origin and development of the warm up (5 items) and the coach profile section (6 items). This instrument was designed to assess the leadership, implementation, desired outcomes and completion level of the warm up. Further, it assessed the origin of the warm-up content and any changes that the coach wished to introduce after their observation of the warm-up. The coach profile section was designed to collect details of the coach's background and qualifications.

4.2.2 Intra-observer reliability

Time-and-motion analysis (TMA) has been used in hockey by MacLeod et al. (2007) and to study coach behaviour (Smith et al., 1977). However, there is a paucity of research on warm-ups and therefore on TMA of warm-ups. Other studies in this area have used questionnaires (e.g. Fradkin et al., 2003). Observations were preferred to evaluate current warm up practice to increase of observing the real practice.

In the current study, a pilot test was completed to ensure familiarity with the method and to ensure intra-observer reliability. To assess reliability, a live observation was performed and simultaneously filmed using a video camera (Panasonic HC-W580EB-K, Japan). After a forgetting period (two weeks), the recorded observation was analysed. This process of a forgetting period followed by re-analysis was repeated (Appendix 4.4). The similarity between the three observations was tested with the application of a Pearson product moment analysis. The results showed a high correlation between the three observations (Table 4.4) (Field, 2009).

Table 4. 4 Intra-observer reliability of allocation of RAMP and warm-up/skill rehearsal categories to repeat views of warm-up

Reliability test	Observation number	Pearson product moment
RAMP	Live vs. Repeat 1	0.99
	Live vs. Repeat 2	0.99
	Repeat 1 vs. Repeat 2	0.97
	Live vs. Repeat 1 vs. Repeat 2	0.99
Warm-up/skill rehearsal	Live vs. Repeat 1	1.00
	Live vs. Repeat 2	1.00
	Repeat 1 vs. Repeat 2	1.00
	Live vs. Repeat 1 vs. Repeat 2	1.00

4.2.3 The researcher's background

Kawulich (2005) indicates that the background of the researcher has an influence on observations that are made during observational research. The researcher who conducted the observations and who is also the author of this thesis is suitable to observe warm ups. This is due to the considerable experience in sport and exercise science and in hockey specifically. The researcher has been a lecturer for over ten years and teaches with a focus on coach improvement after obtaining a degree in sport and exercise science and a MSc in coaching studies. As a hockey player for 30 years at many levels up to international, the author has been awarded several coaching qualifications up to Level 3 and has been an active coach and coach educator for the last 20 years. The researcher has been involved in national teams as a coach, manager and video analyst and holds an umpiring licence.

4.2.4 Data collation and analysis

The data were collated and subsequently assigned to categories; initially into pulse raiser and skill rehearsal and then into RAMP categories (to assess aim 1 and objective 1). The collated data were compared by gender (male vs. female), level (national, regional or district leagues) and by qualification (qualified vs. unqualified hockey coaches) in each case (to assess objective 2). The analysis was initially performed on Microsoft Excel® and then by use of SPSS® (IBM® SPSS®, 2015). Initially, the data were assessed for normality (Shapiro-Wilks) before a t-test was applied to the groupings of pulse raiser and skill rehearsal; to gender, RAMP and gender, pulse raiser and skill rehearsal; and to qualified vs. non-qualified coaches. A one-way analysis of variance (ANOVA) test was applied to the RAMP and gender/performance levels, to each level of qualification vs. pulse raiser and skill rehearsal, to qualification/non-qualification and RAMP, and to each level of qualification vs. RAMP. A narrative approach was taken to assess the coaches' perception of warm ups (aim 2 and objective 3).

4.3 Results

The warm-ups were observed in each stratum for both genders — 18 observations in total — and observations were conducted in most of the leagues of Scottish Hockey during the 2014/15 season (Table 4.5). Six observations were performed in the national league, three in the regional leagues and eight in the district league, with one in the student sports leagues. The observations also covered each of the hockey geographical areas of Scotland (Table 4.6). Two observations were conducted in the north region, 13 in the east, two in the west and one each in the midlands and south. When it was possible, more observations were carried out in the leagues and areas in which there were more hockey teams.

Table 4. 5 Breakdown of observations by league and gender (no of observations)

League	Men	Women
National 1	1	2
National 2	1	1
National 3	-	1
Regional		
- North	0	0
- 1	2	1
- 2	0	0
District Premier	0	1
District 1	0	1
District 2	1	1
District 3	2	1
District 4	-	1
British Universities and Colleges Sport	-	1
Total	7	11

Table 4. 6 Regions in which the observed teams were based

	Region					
Gender	**North**	**South**	**East**	**West**	**Midland**	**Total**
Men	1	0	3	2	1	7
Women	1	1	7	1	1	11

The coach of each team was asked to complete a questionnaire. Most of the coaches (n = 17 with one no response) completed the questionnaire after their team had completed the warm-up. There were 11 male and seven female coaches. There was a wide spread of ages among the coaches; the mode age range was 36-40 years and experience (mode = 2-5 years). The majority of the coaches were qualified (n = 11). One coach had an entry level qualification (Leaders Award), four coaches held Level 1 certificates, three held Level 2 and three held Level 3 certificates. The coaches performed their duties for several hours each week (mode = 3 hours per week) throughout the hockey season (mode = 24-32 of a potential 45 weeks per year). More coaches were active at the district league stratum of Scottish Hockey compared with other levels (n = 6), followed by the regional league (n = 4).

Table 4. 7 Coach characteristics

Category	**Sub Category**	**N**	**Sub Category**	**N**
Gender	Male	11	Female	6
			No response	1
Age	18-25	3	46-50	2
	26-30	1	51-55	2
	31-35	2	55+	1
	36-40	6	No response	1
Years coaching hockey	< 1	2	11-15	4
	2-5	7	16-20	1
	6-10	3	No response	1
Qualifications	None	6	Level 2	3
	Leaders	1	Level 3	3
	Level 1	4	No response	1
Hours coaching per week	1.5	1	12	1
	3	3	15	1
	4	2	25	2
	5	2	25+	0
	6	1	No response	3
	10	2		
Weeks coaching per year	10	1	32	2
	16	1	40	1
	20	1	40-45	1
	24	2	45	2
	26	2	No answer	3
	30	2		
Standard coaching level*	District	6	Nat league 3	1
	Regional	4	International	1
	Nat league 1	1	No response	3
	Nat league 2	2		

*Level at which most of each participant's coaching is performed

The results detail in two distinct ways the time that was spent in each of the phases of a warm-up. First, the warm-up session was divided into a warm-up and a skill rehearsal and these periods were combined to produce a total. Second, parts of the warm-up were classified as RAMP sub-sessions. This breakdown was calculated according to gender, level and coach qualification. The types of stretches and activities that were carried out within the warm-up were also detailed. Subsequently, a summary of the coach profile and the answers that were given to the post-warm-up questionnaire were included.

Prior to the analysis below, the data were assessed for normality by Shapiro-Wilk (Table 4.8). Across all variables, the data were normally distributed ($p > 0.05$).

Table 4. 8 Test of normality (Shapiro-Wilk)

Variable	Statistic / degree of freedom	Significance (p-value)
Warm-up	0.914 / 18	0.101
Skill rehearsal	0.934 / 18	0.228
Raise	0.927 / 18	0.173
Activate / mobilise	0.952 / 18	0.452
Potentiate	0.940 / 18	0.285

The results of the observation (Figure 4.1) show that the mean (95%CI) warm-ups were performed for 8.38mins (1.94-14.8mins) and 14.5mins (9.8-19.2mins) for males and females respectively. The skills rehearsals were performed for 12.0mins (6.8-17.2mins) and 8.8mins (4.7-12.9mins) for males and females respectively. The total periods were 20.38mins (12.7-28.1mins) and 23.3mins (16.1-30.5mins) for males and females respectively. There were no statistically significant differences between genders in respect of each aspect of the warm-up (independent t-test: warm-up: $t(15) = 0.78$, $p = 0.939$, 95%CI = -6.19-6.66; skills rehearsal: $t(15) = -0.99$, $p = 0.334$, 95%CI = -10.74-3.88; total: $t(15) = -0.685$, $p = 0.334$, 95%CI = -14.33-7.35).

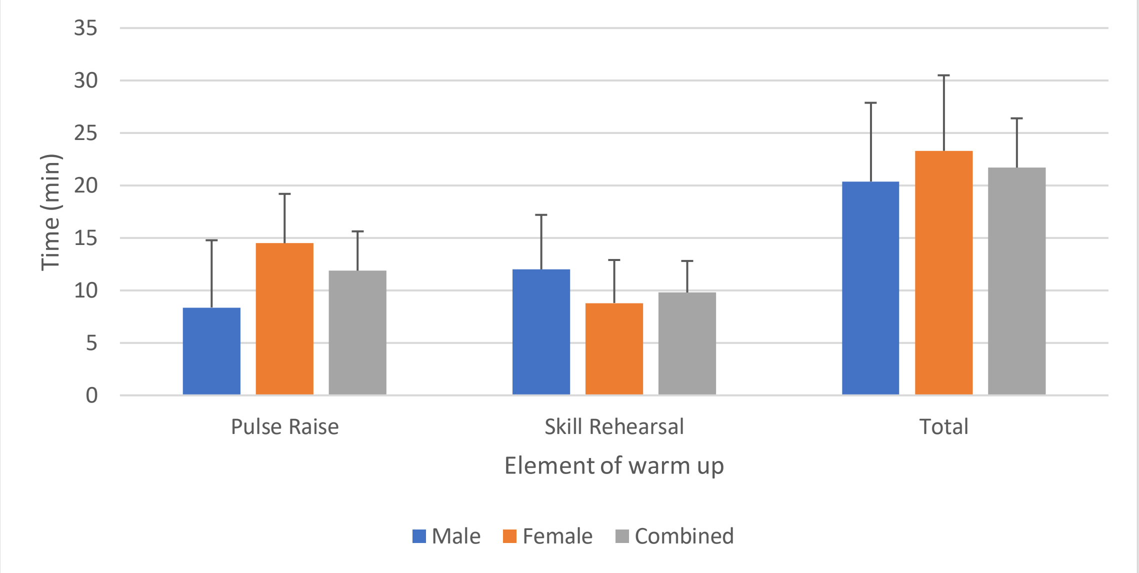

Figure 4. 1 Breakdown of content of hockey warm-up by gender (mean) (95%CI)

An analysis of the time spent in each element at each level (Figure 4.2) shows that the warm-ups were performed for 9.17mins (3.7-14.6mins), 10.33mins (2.4-18.3mins) and 16.42mins (7.7-25.2mins) at the district (with the British Universities and Colleges Sport (BUCS) team), regional and national levels respectively. The skills rehearsals were performed for 9.5mins (4.4-14.6mins), 8.67mins (-16.8-34.2mins) and 12.08mins (9.4-14.8mins) for the district (with BUCS), regional and national levels respectively. The total session times were 18.67mins (12.1-25.3mins), 19.0mins (-7.2-45.2mins) and 28.5mins (19.8-37.2mins) for district (with BUCS), regional and national level teams respectively. A comparison, through application of a one-way ANOVA, shows no significant differences in the durations of each section according to performance level (warm-up (F(2, 14) = 0.479, P = 0.629); skills rehearsals (F(2, 14) = 0.199, p = 0.822); total (F(2, 14) = 0.102, p = 0.904).

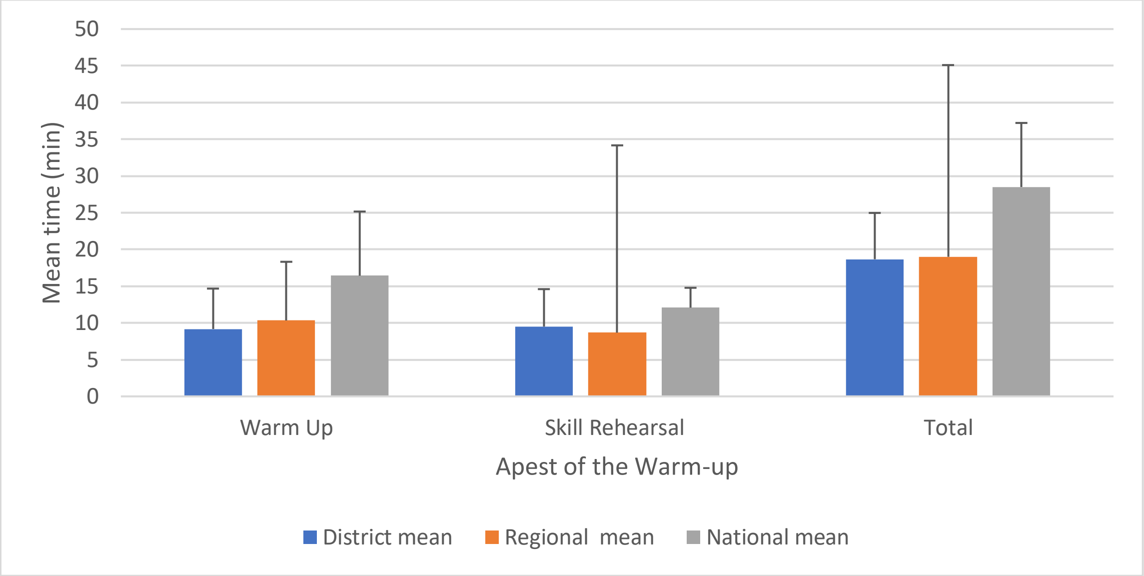

Figure 4. 2 Breakdown of content of warm-up by performance level (mean) (95%CI)

A comparison by gender of the duration of each section according to the RAMP principles (Figure 4.3) shows that the raise element lasted for 1.86mins (0.52-3.2mins) and 2.4mins (1.5-3.3mins) for males and females respectively. The activate/ mobilise element lasted for 7.81mins (4.1-11.5mins) and 10.5mins (7.5-13.5mins) for males and females respectively. The potentiate element lasted for 5.94mins (1.3-10.6mins) and 8.4mins (5.3-11.6mins) for males and females respectively. Finally, the recovery section took up 4.81mins (2.0-7.6mins) and 4.7mins (1.5-7.9mins) for males and females respectively. There were no statistically significant differences between males and females (independent t-test: raise: t(15) = 0.348, P = 0.733, 95%CI = -1.355-1.89; activate and mobilise: t(15) = 0.947, P = 0.358, 95%CI = -2.45-6.38; potentiate: t(15) = 0.783, p = 0.446, 95%CI = -3.19-6.91; recovery: t(15) = -0.214, p = 0.833, 95%CI = -4.92-4.02).

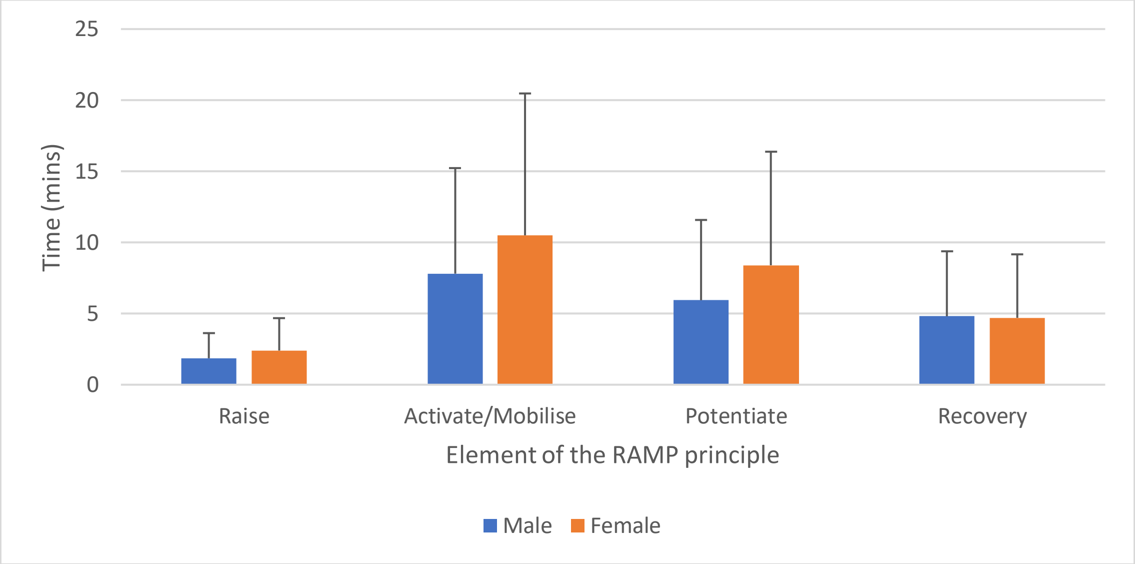

Figure 4. 3 Breakdown of time spent in each element of the RAMP principle by gender (mean) (95%CI)

A comparison of the duration of each of the sections that were classified according to the RAMP principle (Figure 4.4) across performance levels shows that the raise elements lasted for 2.22mins (0.9-3.5mins) for the teams at district and BUCS levels, 3mins (-0.3-7.3mins) for the regional level teams and 1.67mins (1.0-2.3mins) for the national level teams. The activate and mobilise sections took up 9.17mins (4.9-13.4mins) for the district and BUCS level teams, 6.83mins (4.2-9.4mins) for the regional level teams and 10.75mins (7.5-14.0mins) for the national level teams. The potentiate sections lasted for 6.06mins (1.7-10.5mins) for the district and BUCS teams, for 5.3mins (-7.2-17.8mins) for the regional level teams and 10.17mins (7.6-12.8mins) for the national level teams. Lastly, the recovery sections lasted for 5.1mins (-20.5-7.8mins) for the district and BUCS, 4.33mins (-7.6-16.3mins) for the regional level and 4.42 (-0.7-9.5mins) for the national level teams. There were no significant differences in the duration of each section level (ANOVA: raise: F(2, 14) = 0.903, p = 0.428; activate and mobilise: F(2, 14) = 2.492, p = 0.119; potentiate: F(2, 14) = 1.381, p = 0.283; recovery: F(2, 14) = 1.381, p = 0.988).

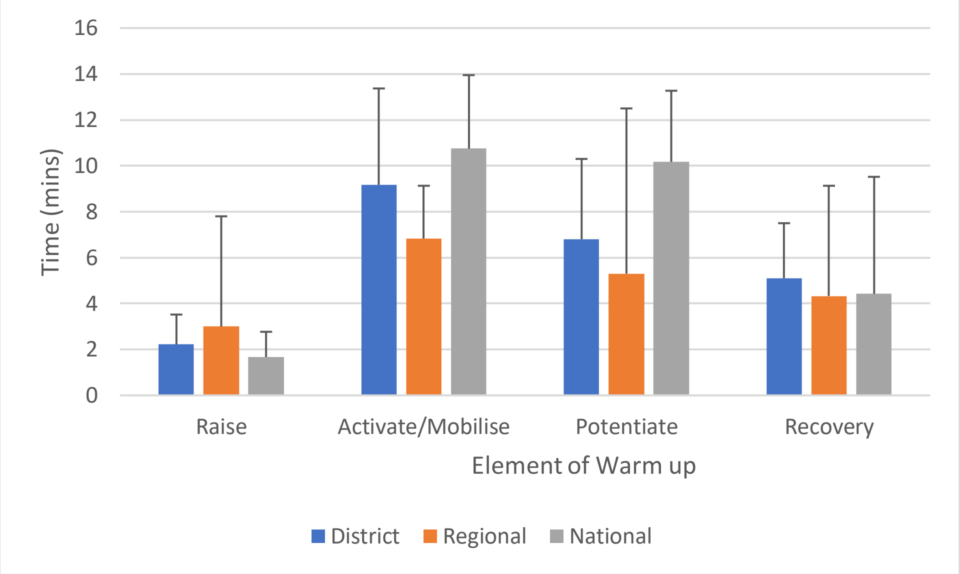

Figure 4. 4 Breakdown of time spent in each element of the RAMP principle by performance level (mean (95%CI)

An analysis of the warm-ups that were followed by teams that had qualified coaches compared with those that had unqualified coaches (Figure 4.5) shows that the pulse-raise sections lasted for 12.77mins (7.6-17.9mins) for teams with qualified and 10.58mins (1.9-19.3mins) for teams with unqualified coaches. The skills rehearsal sections lasted for 9.41mins (5.6-13.2mins) and 11.75mins (3.9-19.6mins) for teams with qualified vs. those with unqualified coaches respectively. The total session times were 22.18mins (15.7-28.6mins) and 22.33mins (10.8-33.8mins) for teams with qualified vs. those with unqualified coaches respectively. There were no statistically significant differences between the groups (independent t-test: warm-up: t(15) = -1.127, p = 0.278, 95%CI = -12.28-3.78; skills rehearsal: t(15) = 0.974, p = 0.346, 95%CI = -3.56-9.56; total: t(15) = -0.252, p = 0.804, 95%CI = -11.8–9.3). The coaches who had qualifications were found to conduct similar length warm-ups and the difference was not statistically significant.

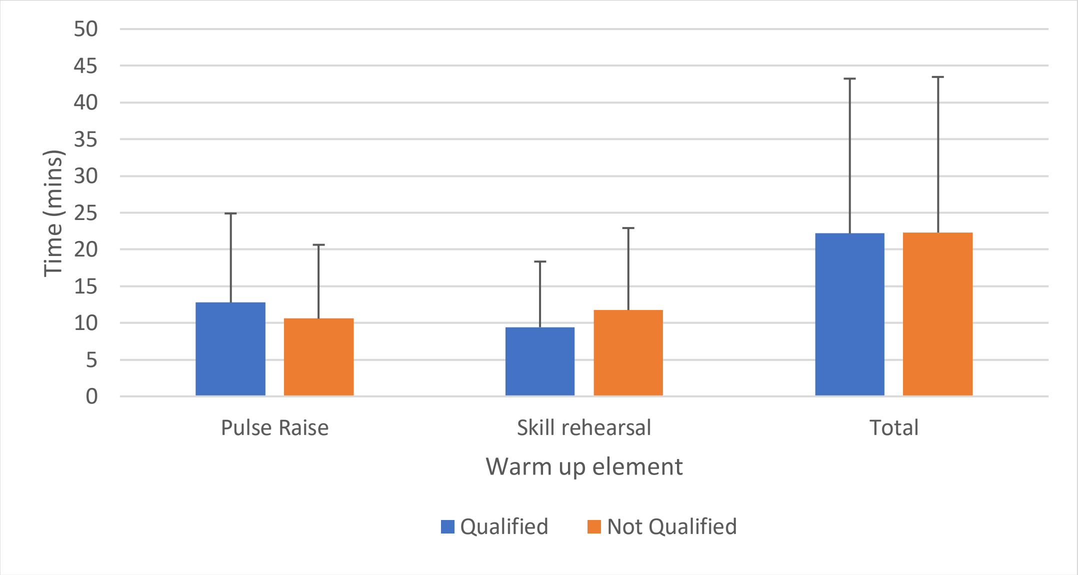

Figure 4. 5 Time spent in each element of the warm-up - qualified versus non-qualified coaches (mean) (95%CI)

When level of qualification is considered (Figure 4.6), the warm-up section was found to last for 10.58mins (1.9-19.3mins), 24.0 (14.2-33.8mins), 12.13mins (3.5-20.8mins), 15.25 (3.1-27.5mins) and 3.5mins (-2.9-9.9mins) for teams who had coaches with no qualifications or awards at Leaders, Level 1, Level 2 and Level 3 stages respectively. A one-way ANOVA shows that there were no significant differences between the stage of qualification and the duration of each element of the warm-up (between-group analysis for the pulse raiser: F(5, 12) = 1.385, p = 0.297; skills rehearsal: F(5, 12) = 0.353, p = 0.870; total: F(5, 12) = 0.331, p = 0.881.

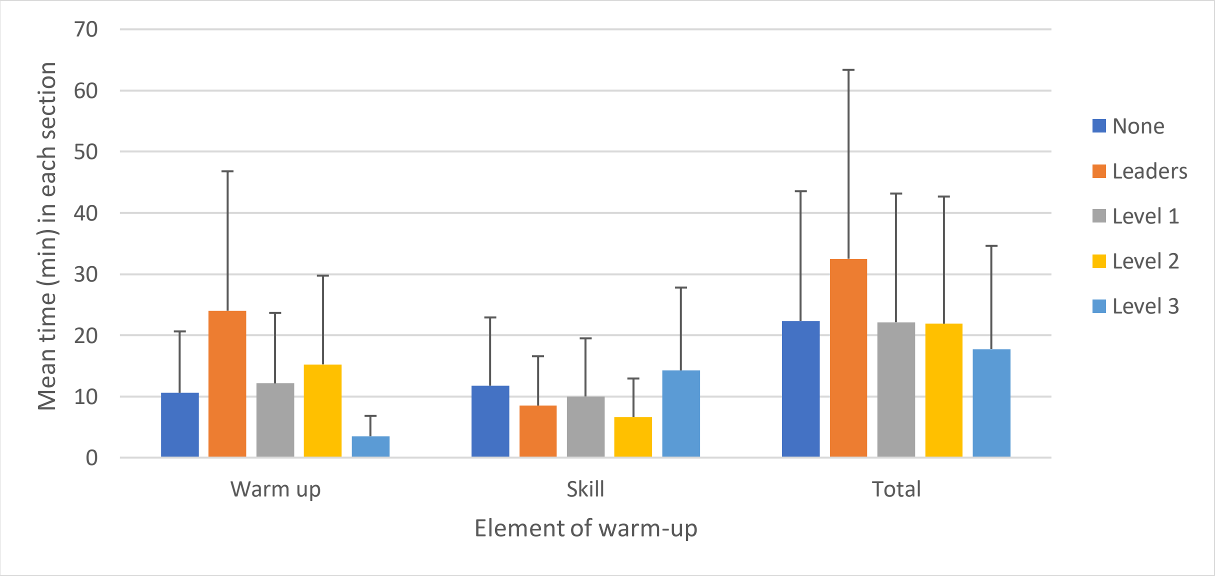

Figure 4. 6 Time spent in each element of the warm-up as classified by RAMP principle and coach qualification (mean) (95%CI)

An analysis of the duration of each section, classified according to the RAMP principle, between those with hockey coaching qualifications and those without (Figure 4.7) shows that the raise section lasted for 2.08mins (1.1-3.1mins) and 2.18mins (1.0-3.3mins) for teams with unqualified and qualified coaches respectively. The activate and mobilise section lasted for 10.17mins (4.1-16.2mins) and 9.0mins (6.4-11.6mins) for teams with unqualified and qualified coaches respectively. The potentiate section lasted for 5.83mins (-0.7-12.4mins) and 7.86mins (4.9-10.9mins) for teams with unqualified and qualified coaches respectively. The recovery section lasted for 5.67mins (1.4-5.6mins) and 3.5 (1.4-5.6mins) for teams with unqualified and qualified coaches respectively. There were no statistically significant differences between the groups (raise: F(2, 15) = 1.316, p = 0.298; activate: F(2, 15) = 0.945, p = 0.411; potentiate: F(2, 15) = 1.256, p = 0.313; recovery: F(2, 15) = 3.637, p = 0.52).

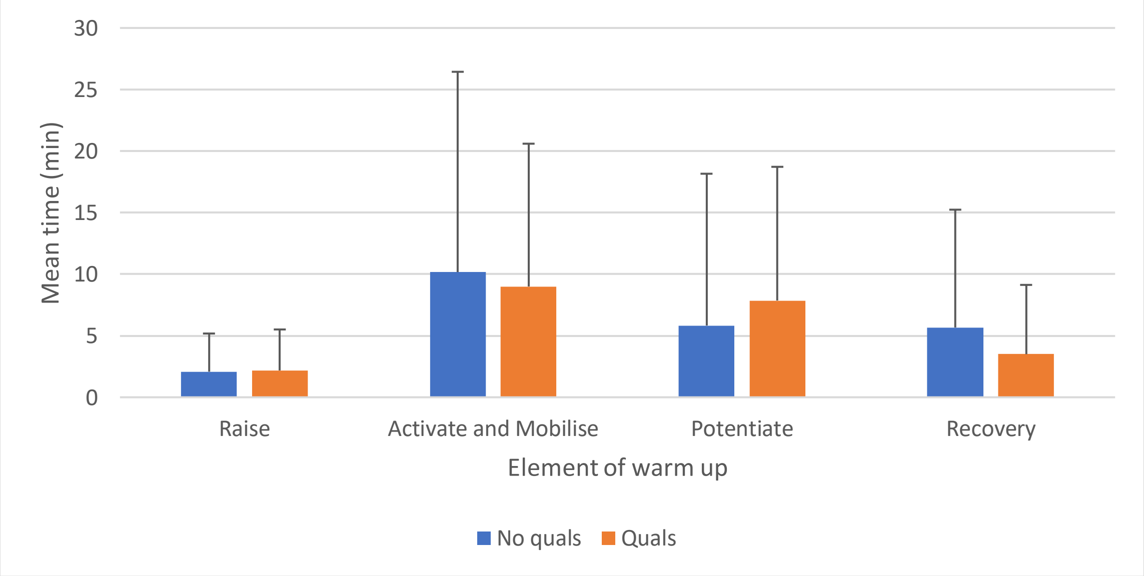

Figure 4. 7 Time spent in each element of the warm-up - qualified versus non-qualified coaches (mean) (95%CI)

An analysis of the warm-up according to the RAMP principle by level of qualification of the coach (Figure 4.8) shows that the time spent in the raise section was 2.08mins (1.7-3.1mins), 5.0mins (5-5mins), 1.88 (1.5-2.3mins), 2.88 (0.1-5.7mins) and 0.00 (0.0-0.0mins) for teams with coaches who had no qualifications or who had Leaders, Level 1, Level 2 and Level 3 grades respectively. The time spent in the activate and mobilise section was 10.17mins (4.1-16.2mins), 5.0mins (5.0-5.0mins), 11.5mins (7.6-15.3mins), 9mins (2.2-15.8mins) and 6.0mins (-32.1-44.1mins) for teams with non-qualified coaches or those with Leaders, Level 1, Level 2 and Level 3 qualifications respectively. The potentiate section lasted for 5.83 (-0.7-12.4mins), 16.0mins (16.0-16.0mins), 7.37mins (5.6-9.1mins), 9.5mins (4.2-14.8mins) and 1.5mins (-17.6-20.6mins) for teams without qualified coaches or with coaches qualified to Leader, Level 1, Level 2 and Level 3 grades respectively. The recovery section lasted for 5.67mins (1.7-9.6mins), 1min (1.0-1.0min), 3.63mins (-0.6-7.8mins), 4.0mins (-2.4-10.4mins) and 3.5mins (-41.0-47.0mins) for teams with coaches who had no qualifications or awards at Leader, Level 1, Level 2 and Level 3 grades respectively. There were no statistically significant differences (one-way ANOVA analysis) in the time that was spent in each section between the groups (pulse raiser: F(5, 12) = 2.213, p = 0.121; activate and mobilise: F(5, 12) = 0.495, p = 0.774; potentiate: F(5, 12) = 1.465, p = 0.272; recovery: F(5, 12) = 1.043, p = 0.437).

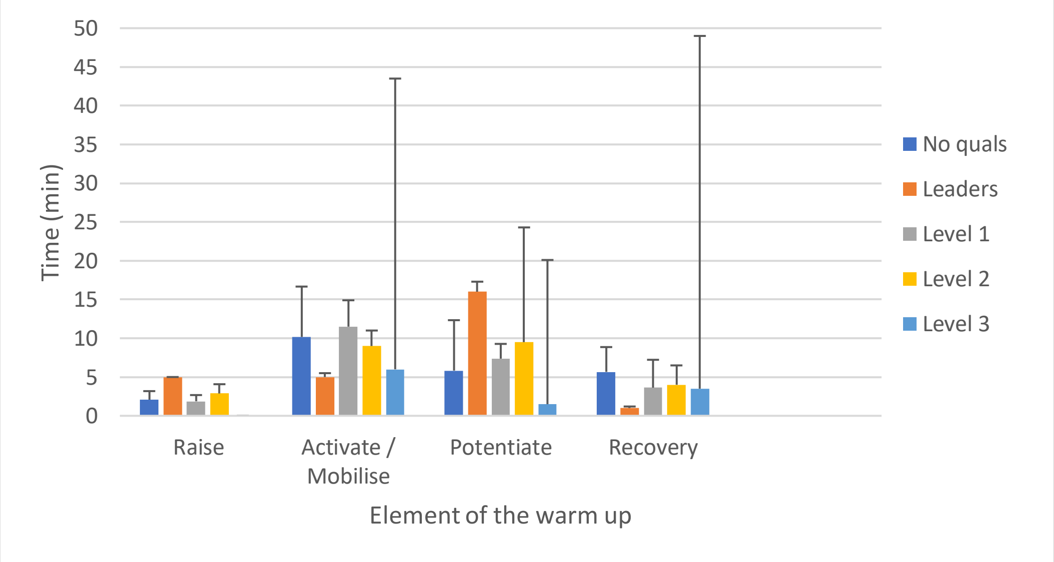

Figure 4. 8 A breakdown of each section of the warm-up according to the RAMP principle and qualification level of the coaches (mean) (95%CI)

Table 4. 9 Comparison of actual warm-up content compared with recommended

Element of warm-up	How often seen in this study (%)	Mean time in this study (min) (SD)	Avest (2010) Mean time (min)	Bishop (2003) or Cone (2007) time in each phase (min)
Raise	88	2.2 (1.4)	2.7	3-5*
Activate/Mobilise	100	8.4 (4.3)	12	7#
Potentiate	88	8.5 (4.9)	21	11.5#
Recovery	70.5	4.4 (3.9)	-	5*
Total	-	23.5 (3.8)	35.7	21.3-23.5∞

*from Bishop (2003); #from Cone (2007); ∞ excludes recovery

Table 4.9 shows the comparison between current warm up practice in hockey in Scotland compared to the literature. Regarding performance of stretch and NMT exercises, Table 4.10 shows that static stretching during the warm-up is common at all levels. However, performance of NMT exercise appears to occur less frequently. Table 4.11 summarises the type and frequency of activities in warm ups.

Table 4. 10 The frequency of static stretching and neuromuscular exercises

Level	**Static stretches (no. of sessions/total sessions observed)**	**Neuromuscular exercises (no. of sessions/total sessions observed)**
BUCS	1 / 1	0 / 1
District	4 / 8	1 / 8
Regional	1 / 3	0 / 3
National	2 / 6	1 / 6
Combined (%)	8 / 18 (44.4%)	2 / 18 (11.1%)

Table 4. 11 Numbers of hockey activities performed during the warm-ups

Activity	**Number of sessions in which activity observed**	**% of total sessions observed**
Warm ups with no hockey at all	6	33
Warm ups with just static skills	4	22
Drills	5	28
Small-sided games	3	17

4.3.1 Results of post-warm-up coach questionnaire

This questionnaire was completed by 17/18 coaches of the teams who undertook the observed warm-ups. The results are summarised in Table 4.12. The coaches who volunteered for this study varied in age from 18 years old to more than 55 years (the majority were between 36-40 years old). Their experience levels varied but most had worked as coaches for 11-15 years. The majority of coaches were male (10/17) and several male coaches coached female teams (n = 3). More coaches were qualified (n = 11) and some had no formal qualification (n=6). Most coaches were deployed for between three and 10 hours per week for the hockey season (26-30 weeks per calendar year). More coaches in this study were involved at the lower levels (district) than at higher levels such as in the national league, which was proportionate to the number of teams that play at this level, i.e. there are many more teams in the district leagues than in the regional or national leagues.

The results show that most coaches devised the warm-up for their teams and the most popular desired outcomes were the quickening of the pulse, mental preparation and stretching. Most of the coaches developed the warm-ups from exercises they had always done, or they copied others, had undertaken coach education, had talked to other exercise professionals and/or had undertaken sports-related courses.

Only half the warm-ups were performed as desired; coaches reported that the most frequent omissions were position-specific exercises and those designed to improve intensity, focus and proprioception, and some commented that the sessions were shorter than they wished. A number of reasons were given for the omissions but there was no stand-out answer. Coaches reported that in future the warm-ups would include proprioception, position-specific and injury-prevention exercises, small-sided games, and skills rehearsals, and would be of longer duration. Just under one-third of the group had not devised their teams' warm-ups. These coaches reported that this was because they were busy with administration and that warm-ups were conducted by a personal trainer in the team.

Table 4. 12 Summary of the answers given by coaches to the post warm-up questionnaire

Question number	Question	Answers (n=17)	N	Answers	N
1*	Did you prescribe the warm-up?	Yes	12	No	5
2	If not, then who developed it?	No prescribed warm up Captain	2 1	Players with exercise experience Leader changes	1 1
3	Why did you not develop the warm-up?	Doing admin Qualified personal trainer in team Always led by captain	1 1 1	Not applicable as no prescribed warm up	2
4	Desired outcomes	Raised pulse Stretch Ready for skills rehearsal	6 3 1	Mental prep Team building Not answered	4 2 1
5	If coach devised warm-up, was it done as desired? (n = 12)	Yes No	8 3	Not answered	1
6	What was missed out or changed? (n = 3) (Multiple answers available)	Pitch static skills Pitch dynamic skills Time shortened Intensity reduced	1 1 1 1	Pulse raiser Proprioception exercises Small-sided games	1 1 1
7	Why was the warm-up not done as required? (n = 3)	Coach not there Players not bothered Rushing	1 1 1	Players don’t realise importance of warm-up	2
8	Where did you get warm-up from? (Multiple answers possible)	Exercises always done Copying other coaches Coach education Chat to exercise professionals	8 6 5 5	Informed players have exercise experience Exercises players like Other S&C	3 3 3
9	Inclusion in future warm-ups	Proprioception More time More intensity Injury prevention Dynamic stretches More concentration	3 3 3 2 2 2	Position-specific exercises Improved quality Pulse raiser, more quality, nothing	1 1 1 each

*1 questionnaire was not completed

4.4 Discussion

This study aimed to investigate current warm up practice in recreational hockey in Scotland, then compare this data with the current recommendations and explore the coaches' perception of the warm up. This study achieved its aims and the major findings were that the warm ups used by teams across Scotland contained most of the required components of a warm up and are similar in length to those reported in the literature (Avest, 2010; Bishop, 2003; Bishop, 2003a; Cone, 2007). Also, nearly 40% of the warm-ups that were observed contained static stretches, whereas NMT was only observed in two of the 18 observations that were made. The warm-ups that, are devised by the coaches are similar to those used in other sports (Bishop, 2003; Bishop, 2003a; Cone, 2007; Jeffreys, 2007).

The warm-up must be compared with those that have been recommended before more conclusions can be drawn. This comparison is outlined in Table 4.9. The pulse-raiser, potentiate and recovery sections in this were slightly shorter than the recommendations (PR = 2mins in this study, recommended = 3-5mins; potentiate = 8.5mins and 11.5mins respectively; recovery = this study = 4.4mins; 5mins recommended). The activate and mobilise section was slightly longer than recommended (this study = 8.4mins; recommended = 7mins). These are quite small differences and may not affect injury risk or performance, however, this would need further investigation.

The variation in timings of the whole warm-up and the component parts is consistent with the findings of other studies, for example, that by Avest (2010) (Table 4.9). In football, the warm-up duration varied between 15 and 45 minutes (mean 30.8 (SD 8.2) mins). However, the authors of the study on football warm-ups (Towlson et al., 2013) did not report the duration of individual components.

More recently, the 'typical warm-up', as reviewed by Silva et al. (2018), has consisted of a general aerobic warm-up, stretches and sport-specific exercises. Those warm-ups that included multiple sprints (for example 5 x 50m sprints) and maximum leg press or back squats, often at the end of the warm-up session, improved explosive task performance. Furthermore, Silva et al. (2018) found that short warm-ups (five to 12 minutes of general aerobic exercises followed by seven minutes of dynamic exercises) were as effective as long warm-ups to assist with explosive movements such as sprints in football. Completion of 12 minutes of small-sided games improved performance in explosive tasks. Silva et al. (2018) suggested that static stretching was the least effective mechanism for improving sprint and agility performance.

A rest period at the end of the warm-up of up to 5 minutes is recommended so that the participants in the warm-up can benefit from its effects and reduce their levels of fatigue (Bishop, 2003a).

A gender comparison shows (Figure 4.3) that female teams tend to spend longer (although not significantly different) in the raise phase than male teams, whereas males spend more time in all other phases (skills rehearsal, activate/mobilise and potentiate). This could be because males use the skills-rehearsal phase as a bridge between the pulse-raise phase and the activate/mobilise or potentiate phases. There may be a good reason for females to spend longer in the activation and mobilisation phase than males since there is evidence that females suffer knee injuries more frequently than males, even though overall the injury rates are similar between the genders (figure 3.1, chapter 3). In addition, this could be an opportunity for coaches to include some injury-prevention, proprioception or technique-development exercises. NMT for females can have a significant effect on the numbers of ACL injuries; a reduction of up to 73.4% has been reported (Sugimoto et al., 2012).

The potentiate section of the warm-up was found to last for between six and seven minutes in this study. More time was spent on this stage in the more elite leagues. Further investigation is required to establish a possible reason for this. The majority of the potentiation that was observed in this study involved sprints over a distance of approximately 15 metres. Other ways in which potentiation can be introduced include jumping, for example, counter-movement jumps, which generate more force. The optimal duration of this section has been reported as 7–10 minutes (Bevam et al., 2009) and this duration is similar to that being performed. Bevam et al. found that a four-minute recovery period was required between heavy-resistance training and a return to pre-test levels in a task that involved a ballistic bench press and peak power output. This time period was required for creatine phosphate re-synthesis. This recovery time or greater may be required for the muscles of the lower body (Kilduff et al., 2007).

In this study, there appeared to be a trend between the performance level of play and the duration of the warm-up. Those who played in the elite leagues warmed up for longer than those who played in lower leagues, although not statistically significant (district and regional leagues = 15 mins approx. vs. 22.2 mins in the national league). This was especially noticeable in the activate and mobilise phase and the potentiation phase (an extra three min for national league vs. district and regional leagues). Similarly, Avest (2010) showed that warm-ups in semi-elite hockey, which is at a level higher than the teams that were observed in Scottish hockey, lasted longer than those that were observed in this study: 36 vs. 23.3 minutes respectively (Table 4.9). The greatest difference between the two studies was found in the amount of time that was spent in the activate and mobilise phase (12 vs. 8.4 mins) and particularly in the potentiate phase (21 vs. 8.5 mins). Avest (2010) also investigated the amount of time that coaches would like to spend on a warm-up and found that they would prefer to warm up for longer (mean = ~38 min) than warm-ups generally last.

However, the evidence from Bevam et al. (2009) and Kilduff et al. (2007) suggests that a lengthened warm-up does not affect performance. On the contrary, they found that a shorter warm-up increased the performance of the athletes in sprint and power-based tasks. Therefore, as elite levels of performance require a greater intensity of action and a greater number of sprints than non-elite counterparts (Jennings et al., 2012), it could be beneficial for these athletes to undergo a short warm-up.

Previous investigations into warm-ups in football suggest that they are of longer duration than the average that was observed in this study. The average duration of warm-ups in professional football is approximately 31 minutes with a wide range (15–45 mins). Typically, these warm-ups include a recovery period of 12.4 minutes before the match starts (Towlson et al., 2013). McGowan et al. (2015) suggest that warm-ups in team sports should be shortened to around 16 minutes and end with small-sided games rather than long tasks (22 mins) since these long tasks deplete energy (Behm et al., 2001) and decrease the body’s heat storage capacity (Gregson et al., 2005).

The pulse-raiser element of the warm-up that was observed in this study lasted for just under two minutes. The benefits of this section are summarised by McGowan et al. (2015). Muscle temperature increases with exercise and reaches an equilibrium after approximately 10 minutes, depending on the exercise intensity (Price and Campbell, 1997); joint resistance decreases with an increase in temperature and therefore the stiffness of muscle fibres is reduced (Shellock & Prentice, 1985). The increase in temperature speeds up the release of oxygen from haemoglobin, and there is a similar pattern but a smaller effect with myoglobin. Furthermore, there is an increase in the delivery of blood due to vasodilation of the muscle blood vessels (McArdle et al., 2000). The increase in temperature also increases the speed of rate-limiting oxidative reactions (Jones et al., 2006). The increase in muscle temperature increases central nervous system function and the speed of neural impulses (Woods et al., 2007). One of the few disadvantages of warming up is the effect on heat-storage capacity (Racinais et al., 2017).

The active process of warming up ensures that the muscle contracts, and if this is performed with progressively intense exercises and with the addition of either sprint or maximal voluntary contractions, the performer benefits from post-activation potentiation if we assume no fatigue (Hodgson et al., 2005). Lastly, during rest, myosin and actin form stable bonds and make the muscle feel stiff (Enoka, 2000). With movement, the number of bonds is reduced, and this reduces passive stiffness and increases the rate of force development and power (Bishop, 2003a). In this study, the temperature-raising section (as opposed to skill rehearsal) lasted for approximately the recommended length of time (~12 min) or about 11 minutes in the RAMP principle format (pulse raiser with activate and mobilise); therefore at least theoretically, the athletes should benefit from the advantages discussed above.

However, warm-ups that were observed in this study contained static stretches (41%), especially in the lower leagues (44.4%). This contrasts with the 11.7% of warm-ups that contained NMT. Interestingly, Avest (2010) observed that 77% of the warm-ups that were investigated in that hockey study contained static stretching and that 100% of the warm-ups also contained dynamic stretches (NMT was not recorded). The results in this study were in line with some of the answers that were given in the coach questionnaire in the current study (Table 4.12). No coaches reported that injury prevention was a desired outcome of the warm-up. These findings are similar to those reported by Towlson et al. (2013). However, the coaches acknowledged that proprioceptive exercises were missing from the warm-ups. They also reported a lack of intensity, which could be equated with the lack of time that was spent in the potentiation element of the warm-up. The exercises that coaches wished to include in future were related to NMT; greater quality, more time and proprioceptive exercises.

The amount of static stretching that was performed was surprising given the quantity of research that supports the exclusion of this type of stretching. In a systematic review of high-quality studies, Behm and Chaouachi (2011) indicated that performance during 50 tests was significantly impaired after static stretching in 42 studies compared with ten in which significant improvement was reported when force, power and strength were required. Hence there appears to be strong evidence of the negative effects of static stretching. However, this may be mitigated if static stretches are combined with other elements of the warm-up (Young, 2007). Static stretching increases the compliance of the musculotendinous unit (MTU) which, whilst it increases the range of motion, can decrease the capacity of the MTU to generate force. Static stretches can alter the relationship between the length and tension and subsequently the relationship between the angle and the torque (Marek et al., 2005). This primarily affects actions that involve fast muscle contraction, rely on cycles of stretch and shortening or have short contact time with the ground (Behm and Chaouachi, 2011).

Skills rehearsal, which involves the performance of the skills of the sport before competition can be in the form of playing small-sided games to replicate the impending competition. Such activities stimulate neural pathways and increase neuromuscular activation (Gabbett, 2008) and they simulate the skills, movements and psychological requirements of the sport in question (McGowan et al., 2015). The frequency of performance of small-sided games in this study was just 17%; more teams (33%) did not practice hockey within the warm-up (Table 4.11). Some teams performed skills in a static manner (22%) while 28% rehearsed skills actively but without taking part in a small-sided game, i.e. they practised skills in a pre-determined format (a drill). The rehearsal of skills could aid mental preparation as well as physical. Coaches in the Avest (2010) study indicated that mental preparation was important and should contribute to this element of a warm-up. Indeed, 25% of coaches in this study indicated that mental preparation was the desired outcome of a warm-up.

NMT was only observed in two of the 18 warm-ups in this study. It was observed in a warm up by a Level 3 in the Men’s National league I and by a Level 1 coach in the Women’s District league. NMT was not listed in the only other study that has been performed in this area (Avest, 2010). However, coaches in the current study reported that they would like to include proprioception and injury-prevention exercises in future warm-ups. They also indicated that they would extend their warm-up time and include dynamic stretches and greater quality. Therefore, there appears to be an opportunity to include NMT, which has been shown to have considerable benefits in both performances (Noyes et al., 2013; Weir et al., 2019) and injury prevention (Sugimoto et al., 2012). The changes in kinematics that follow NMT can improve trunk (Sasaki et al., 2019), hip (Hewett et al., 2017) and knee flexion, and knee abduction (Hopper et al., 2017; Myer et al., 2008) through alterations in muscle activity. Performance of NMT increases activation of the gluteal muscles (gluteus maximus and medius) (Weir et al., 2019), the hamstring, especially the semitendinosus (Zebis et al., 2015), and the gastrocnemius (Hurd et al., 2006; Lee et al., 2014). Another benefit is the reduction in vGRF (Padua & DiStefano, 2009). These benefits are discussed in more detail in section 2.7 of the literature review and in Study 3.

Generally, there was a dearth of small-sided games activity in the warm-ups that were observed and, therefore, improvements could be made to improve both physical fitness and technical performance. In volleyball, Gabbett (2008) demonstrated the usefulness of instructional training and small-sided conditioning games to improve technical ability and sport-specific fitness (vertical jumping, speed agility, upper body muscular power and estimated maximal aerobic power). The study found that instructional training improved technical competence more than skill-based conditioning games did, whereas the latter improved sport-specific physical fitness more than was achieved with instructional training. Therefore, they suggest the application of a combination of instructional training and skill-based games to develop technical competence and sport-specific fitness. One could apply this process to hockey and, logically, gain similar benefits.

The recovery element of a warm-up is another important part of this process. Some studies recommend a small break of about five minutes (Marinho et al., 2017) between the end of the warm-up and the start of the match, while others recommend that the warm-up be completed as close to the start of the competition as possible (McGowan et al., 2015). A small break to allow for the replenishment of energy substrates — adenosine tri-phosphate with creatine (ATP-Cr) —must be longer than five minutes, as ATP-Cr cannot be replenished in this time (Gastin, 2001), thus necessitating a longer break (up to 12min) (McGowan et al., 2015). However, this may have detrimental effects with regard to muscle temperature. In all levels of hockey, the warm-up occurs just before the start of the game and there are no mandatory procedures, such as walk-outs, that must be completed prior to the beginning of the match. This is in contrast with other sports that at the elite level have a much longer break between the warm-up and the match. In football, there is evidence to suggest that warm-ups are completed at least ten minutes before the kick-off (mean = 12.4 min Towlson et al., 2013), which is described as ‘sub-optimal’ by Taylor and Garratt (2010).

In this study, there were various circumstances under which the warm-ups took place; some warm-ups were supervised or led by the coach (qualified and non-qualified), some coaches were not present at all, some warm-ups were led by exercise professionals and in other instances, athletes were asked to perform their own individual warm-ups. The overall time that was spent on the warm-ups led by qualified coaches was longer than that spent by non-qualified coaches, although the difference was non-significant (Figure 4.5 and 4.6). The greatest difference was observed in the potentiate section. There was a three-minute difference in the length of the activate/motivate section and the time spent in the raise section was almost doubled. It is possible that a statistical difference would be observed with a greater sample size.

Qualified coaches in Scotland have attained either a Scottish Hockey Level 1 or Level 2 qualification (or the United Kingdom Coaching Certificate (UKCC) equivalent). The guidance that is offered on warm-ups during the attainment of these qualifications indicates that the warm-up should include a pulse raiser and dynamic stretches (UKCC Level 1) (2010). In the Scottish Hockey Leaders course (2010), there is no mention of a warm-up; nor is there in UKCC Level 2 training (2010). In the hockey UKCC Level 3 course booklet (2010), there is no specific advice on warm-ups. The course notes suggest that there should be a low-intensity aerobic activity, dynamic sport-specific movements/mobility exercises and rehearsal of skills. The warm-up, it recommends, should reflect the intensity of the session and the climatic conditions. The advice concludes that “good preparation of the body” is needed prior to performance to minimise injury. Nonetheless, later in the handout, it recommends that players develop strength and core stability to reduce injury risk. The course notes do not specify any exercises or give references to provide practical solutions to coaches for implementation of this general advice.

Other results in the post warm-up questionnaire suggest that the coaches largely devise and implement the warm-ups. This finding is consistent with the work of Avest (2010) and Taylor and Garratt (2010). Both this study and those mentioned determined that very few coaches consulted or used others with greater knowledge, e.g. strength and conditioning coaches or physiotherapists. However, a UK Sport 2001 report — ‘Plan for Sport’ (cited in Taylor and Garratt (2010), encouraged coaches to be open to new forums to gain knowledge as they aimed to increase their professionalism.

Numerous papers have discussed the aims of warm-ups (Bishop 2003a, 2003b; Cone, 2007; Jeffreys, 2007). Specifically, in team sports, Cone (2007) suggested that physical readiness, injury prevention and resilience and performance enhancement were key elements of a warm-up. These were quite similar to the outcomes that were desired by football coaches. Interestingly, players and staff in football ranked injury prevention as an important motivator to complete the warm-up (Towlson et al., 2013), yet it did not appear in the list of the most important benefits to be gained from a warm-up. These were reported to be increased temperature, which increased oxygen consumption and mental readiness, and post-activation potentiation and decreased muscle and joint resistance, while arousal and technical readiness were of lesser importance.

In this study, raising the pulse, mental preparation and stretching were highlighted as the key desired outcomes. Injury prevention and performance enhancement were not mentioned as outcomes that were sought through the performance of a warm-up in hockey or on a list of elements that were missing from the participants' own warm-ups. However, the coaches listed some areas for improvement of the warm-up: proprioception and intensity exercises (three responses each), position-specific exercises, skills rehearsals and concentration elements (two responses each). Two coaches considered that the warm-up should be of shorter duration. These self-assessed areas for improvement appear to go beyond the guidance that is contained in coach-education courses. Some coaches reported that they would not change anything about their warm-ups (eight responses). This indicates that they were satisfied with the warm-up even though it did not follow the guidance in coach education or the recommendations that have been made regarding warm-ups by Bishop (2003a, 2003b), Cone (2007) and Jeffreys (2007). The evidence provided may underline the recommendation that was stated earlier that coaches should consult with others such as physiotherapists and strength and conditioning coaches, while some desktop research could be useful to enhance coaches' warm-up provision.

4.4.1 Coaches' reflections on warm ups

This study involved experienced coaches, therefore, experience may not be a primary factor in coaches' awareness of their coaching methods. Indeed, they have had many opportunities to reflect on and review practice sessions and games. Counter-intuitively, coaches' self-reflection may not have considered the warm-up as the most important part of their practice. However, coaches do report that the warm-up that is performed is not always as designed or preferred. At all levels of coaching, including that which is proposed by the International Sport Coaching Framework (ISCF) (ICCE, 2013) and in many coach education manuals, coaches are encouraged to reflect on and review their coaching practice to improve their delivery. This function (learn and reflect) also includes a competency to engage in professional development and innovation. The ISCF also explains that one of the functions of coaching is to shape the environment, which includes ensuring that participants are safeguarded, and the identification and recruitment of staff and resources. To ensure further improvement, coaches could strive to develop these competencies in the context of injury prevention. These approaches to coach education and the fulfilment of the roles or competencies may go some way towards providing hockey players (and participants in other sports) with a context in which injuries could be reduced and/or their precursors could be mitigated.

4.4.2 Study 2 Limitations

Although there was careful consideration to ensure the validity of the data, there are some limitations in this study. One inherent limitation of observational data is the methodological approach; overt observation, although ethically preferable, with advanced warning affords the opportunity for both players and coaches to alter their behaviour and thus affect the data that are recorded. The sample size and its characteristics affect the external validity of the study. There was a consideration of the sample size, selection process and spread across both the genders and the leagues, however, a larger sample size would be desirable. Although an intra-observer reliability test was performed, an inter-observer test could have been implemented to increase the reliability and increase the efficacy in the results. It would have been possible to increase the detail of observations; for example, the number of people who participated in each activity could have been noted or heart-rate data to assess warm-up intensity could have been collected. However, this was not regarded as necessary for the achievement of the aims of the study. However, this could be a direction for future research.

The focus of this study was across all leagues and both genders, whereas future research could focus on gender or level. Furthermore, this study focused on the perceptions of the coach after the warm-up, whereas a future investigation could also explore the perceptions or desires of the players regarding their warm-up. Further, an exploration of strategies to maintain muscle warmth in the event of a break in play, for example this could be from being substituted, an injury or half-time.

4.4.2 Discussion summary

The results from this study suggest that, although some elements of the warm-ups that are performed in hockey are similar to those that are recommended in the literature, other elements could be altered to increase the benefits of performance of a warm-up for hockey players. These include an increase in the total warm-up period, the inclusion of NMT and a reduction in the amount of static stretching. A further recommendation is the frequent inclusion of dynamic skills rehearsals, specifically the inclusion of small-sided games to mirror the physical, technical, tactical and psychological requirements of the sport. In more general terms, the aims of the warm-up must include injury prevention.

In addition, coaches could spend more time on preparation for hockey, especially among less elite teams. Coaches could work with others to develop more beneficial routines and supervise the warm-ups so that all constituent elements are performed correctly. With these recommendations, the warm-up in hockey would provide both an injury-prevention effect and a performance benefit.

4.5 Conclusions

This study has ascertained that warm-ups that are implemented across Scotland in hockey are short in each element, as recommended by the literature. A consequence of this mismatch is that current warm-up practice may not prepare players appropriately for the subsequent game. Static stretching is frequently used within warm-ups and is more commonplace than NMT, which may lead to hindered performance and injury prevention. Therefore, although the current practice is sub-optimal, therefore, it is possible to improve the hockey warm-up procedure.

Given the perceptions of warm-ups among coaches, it is evident that the warm-up is often not performed as prescribed. Coaches would like to include (not exclusively) injury-prevention/proprioceptive exercises and would increase the time and the intensity of the warm-up. Surprisingly, in this context, the aims of the warm-up did not include injury prevention.

Chapter Five: Effects of a novel hockey-specific NMT programme on EMG, kinematics and kinetics of recreational female hockey players (Study 3)

5.1 Introduction

Field hockey (hockey) an Olympic sport since 1908 and played globally by both males and females with 137 affiliated countries and 5 Continental Associations members of the worldwide governing body, the International Hockey Federation (FIH) (International Hockey Federation, n.d.). Hockey, with its unique physiology (Reilly and Seaton, 1990; Reilly and Borrie, 1992) is an invasive, intermittent team sport involving many sudden, quick and explosive actions (White & MacFarlane, 2013), played with a stick and ball, therefore injuries are inevitable.

The injury rate in hockey varies considerably from 0.01 to 90.0 injuries per 1000hrs of play (Barboza et al., 2018) and may depend on the context. The injury rates in practice were reported as 2.5 in practice whereas in games it was 12.3 per 1000 hours (Delfino Barbosa et al., 2019) which was similar to the pattern reported by Dick et al. (2007). The injury rate was reported as higher for elite players with Theilen et al. (2016) reporting between 29.1 (women) and 43.3 (men) per match hours and Rishiraj et al. (2009) reporting 70 injuries per 1000 exposure hours. It appears that the difference between injury rates between indoor and outdoor hockey (3.3 and 4.0 / 1000 hours respectively). Lastly, Corenlissen et al. (2020) in a systematic review, reported some differences in injury rates between youth and adult players (4.9 and 7.9 per 1000 athlete exposures). Noncontact injury rates in this study were 4.09 (females, 4.73; males, 3.47) per 1000 playing hours.

Despite the variation in injury rates, the reported injured body part has more consistency. Most injuries, up to 77% (Barbosa et al., 2018), occurred to the lower extremity. In recreational hockey, injuries to the hamstring (18.6%), knee (13%) and hip and groin (11.8%) were frequent (Rees et al., 2020). The injuries sustained were often muscle strains (23%), contusions (17%), ligament/tendon rupture or sprain (15%) and other (12%) (Hollander et al., 2018). These injuries caused timeloss of 1- 7 days (38%) and 8-21 days (30.5%) and >21 days (31.5%) (Hollander et al. 2018).

There is a dearth of research specifically on the injury rates, mechanism and severity of noncontact injuries, despite the prevalence (up to 74% of all hockey injuries, Delfino et al., 2018). The evidence presented in chapter 3 of this thesis shows that non-contact or modifiable hockey injuries in Scotland occur at a rate of 4.09 per 1000 hours (4.73 for females and 3.47 for males). Also, the evidence indicates that injuries in hockey occur to the lower extremities, especially to knees, hamstrings and ankles, and they are caused by movements such as sidecutting, landing, acceleration and braking in all hockey settings. These injuries led to players with no timeloss (30.3%), 1-2 weeks (19.1%), the next session and 1-week timeloss (13.5%). The evidence from Study 1 suggests there are no differences in age and level of play.

The injury rates in hockey are higher than in other Olympic sports (Hollander et al., 2018), which includes those caused without any contact. This has prompted several authors to suggested further research into injury prevention or neuromuscular control programme (Delfino et al., 2018; Hollander et al., 2018; Rees et al., 2020).

A neuromuscular training (NMT) programme can contain a variety of exercises, including strength, plyometrics, agility, balance and sport-specific exercises with varying preventative effects. The greatest improvement effect on injury rates (without additional equipment such as supports or insoles) is related to strength training (odds ratio (OR) = 0.27), balance training (OR = 0.45), and multi-aspect intervention with balance (OR = 0.46), while sport-specific interventions also have a significant influence on injury reduction (OR = 0.55) (Leppänen et al., 2014). Programmes that include plyometrics have also been shown to enhance injury reduction from an odds ratio (OR) of 0.59 to 0.38 and to boost core stability to 0.95 (compared with a control of 0.327 with core stability/proximal control) (Sugimoto et al., 2015; 2016). These results are supported by Lauersen et al. (2014), who report that strength training reduces injury rates by 69%, a multiple exposure programme decreases injury rates by 38%, and proprioception training reduces the number of injuries by 45%. Interestingly, stretching reduces the numbers of injuries by just 4%. Chapter Two includes an extensive review of studies of NMT exercises and the injury-rate reductions that can be achieved through their application (Chapter Two, section 2.7).

Knee injuries are common in hockey and other invasive, intermittent team sports. Deficits in trunk control have been found to predict knee, ligament and ACL injury risk with 84%, 89% and 91% accuracy respectively (Zazulak et al., 2007). Improved trunk control can reduce the occurrence of ACL injury by decreased trunk extension, while peak trunk flexion can be increased by external rotation moments and impulses with targeted trunk control exercises (Hewett et al., 2017). Similarly, programmes that include plyometric exercises can also significantly reduce both the number of ACL injuries and injury risk. Hewett et al. (1999) found that untrained female athletes were 3.6 times more likely to sustain a knee injury compared with trained female athletes (0.43 per 1000hrs, p = 0.05) and their risk of knee injury was 4.8 times higher than that of male athletes (p = 0.03). However, the incidence of knee injuries in trained female athletes following NMT was similar to that in untrained male athletes (0.12 and 0.09 injuries per 1000hrs respectively, P = 0.86).

Myklebust et al. (2003) found, in a prospective study over 3 years with female handball players, a significant reduction in ACL injuries with NMT (OR= 0.06, p = 0.01). Subsequently, a meta-analysis of high-quality studies shows a significant, up to 67% for noncontact injuries, reduction in ACL injuries (Yoo et al., 2010; Webster & Hewett, 2018). Yoo et al. (2010) suggested that NMT programmes were more effective with plyometric and strengthening exercises. These reductions may be due to an increase in the pre-activity muscle activity of the semitendinosus and a decrease in quadriceps (Vastus Lateralis, VL) activity following NMT with female football handball players (Zebis et al., 2016). The control group in this study increased their VL activity and significantly reduced their semitendinosus activity (Zebis et al., 2016). Therefore, increasing the quadriceps to hamstring ratio and increasing the risk of an ACL injury.

There is good evidence that the inclusion of hamstring strengthening exercises, specifically Nordic hamstring exercises (NHE), contributes to a reduction in the number of hamstring injuries. Both Almeida et al. (2018) and van Dyk et al. (2019) found rates of 0.1/1000 hours for players exposed to NHE and 0.2/1000 hours in those football and team sport players respectively who continued with usual training, i.e. a reduction of 51%. This may be due to the level of activation - 134.3% of maximum eccentric voluntary contraction (Ditroilo et al., 2013) and an increase in strength (Mjølsnes et al., 2004) Also, Seymore et al. (2017) found significantly increased volume and cross-sectional area and a non-significant increase in peak eccentric torque following Nordic hamstring training. Furthermore, NHE elicits a greater rise in EMG and an earlier onset of muscle activation compared to other hamstring exercises (a prone leg curl) (Krommes et al., 2021). However, there were no significant changes to muscle fascicle length or stiffness (Seymore et al., 2017).

Lastly, concerning ankle injuries, specifically ankle sprains, NMT appears to have a significant prophylactic effect (Vriend et al., 2016). Programmes with or without balance boards reduce the risk of ankle injury (RR – 0.60). A meta-analysis by Vriend et al. (2016) showed that the studies that contained a single component, the risk ratio was 0.71, and multi-component programmes showed a greater reduction in the occurrence of ankle injuries (RR = 0.55).

The recommendations for the components of NMT have largely adopted and implemented with female team sport players, such as Gaelic football (and hurling/camogie), handball, netball, football and hockey. Gaelic football players, after a twice-weekly 8-week NMT with technique development programme which included a raise section with running-based movements, followed by an activate section (including core exercises, squats and lunges), and sports specific balance. The programme finished NHE, plyometrics and plant and cut exercises, significantly improved their landing technique (Landing Error Scoring System – LESS) and a moderate improvement in lower extremity stability (via Y-Balance test) (O’Malley et al., 2017). Clinically important improvement in landing technique (especially knee abduction) and dynamic stability could decrease the risk of noncontact injuries.

Further to the injury reductions and muscle activation patterns reported by Myklebust et al. (2003) and Zebis et al. (2008) respectively, other high-quality studies have shown to be effective. Holm et al. (2004) found significant improvements in balance following 1 year of multi-component neuromuscular training with female handball players.

Furthermore, Petersen et al. (2005) found reductions in knee (OR = 0.55), ACL (OR = 0.17) and ankle injuries (OR = 0.55) following Balance-board, jumping training and educational information on injury mechanism in females.

A study evaluating the effectiveness of a multi-component NMT in female netball players reported an 11% reduction in overall injuries with a 6% reduction in ACL injuries (Kearney et al., 2019). These results may have been found because of alteration in the movement mechanics found by Hopper et al. (2017). This study found reductions in knee abduction, internal rotation and significant reductions in vGRF following 6-weeks of neuromuscular training in youth netball players.

Reductions of injuries following NMT were observed with young female football players. Soligard et al. (2008) reported, following a comprehensive neuromuscular programme (containing running, strength, plyometrics, balance and cutting exercises) that replaced the warm up, an odds ratio of 0.71. The intervention group had a significantly lower risk of all injuries, overuse and severe injuries. A subsequent systematic review and meta-analysis which included 6 studies (2 studies with the FIFA 11 and 4 implementing the FIFA 11+ programme) show a reduction of injuries (IRR = 0.75) with the FIFA 11+ programme having a greater effect (IRR = 0.61) (Thorborg et al., 2017). The NMT injury reduction programme in floorball had an even greater effect (IRR 0.34). A large scale, high-quality study in a sport described as “hockey played indoors” (Pasanen et al., 2008, p1) found significant reductions in all lower extremity injuries (Pasanen et al., 2008).

There was a suggestion by Delfino et al. (2018) that injuries in hockey could be reduced with a NMT programme. In a subsequent study, Barboza et al. (2019), in a quasi-experimental study, implemented a multi-component NMT programme for 1 season with youth club hockey players 135 players in the control group, 156 players in the intervention group, age = 11.2 – 13.2 years) and found a non-significant decrease in lower injury rates in youth hockey players (a hazard ratio of 0.64). However, a decrease of the burden of injury in the intervention group (a mean decrease of 8.42 days lost) (Barboza et al., 2019).

Another study, at the other end of the performance spectrum, implemented a NMT programme with elite female hockey players (n = 26) focussing on knee injuries (Weir et al., 2019). A biomechanically-informed progressive injury prevention programme, with balance (including arabeques and cross-over lunges), squats, plyometrics (including star jums, box jumps and broad jumps) and core stability exercises (including overhead and lateral ball throws) designed to reduce ACL injury rates was performed for 9 weeks intensively and 16 of maintenance after a control season. The programme increased the total muscle activation of the gluteals by 30% and 30% reduced in peak knee valgus in the high-risk athletes during an unanticipated sidecut. There were also performance benefits; improved upper body strength speed and aerobic capacity (Weir et al., 2019). Therefore, these findings suggest that neuromuscular training can affect the predictors of injury in recreational female hockey players (see 2.4 and 2.5) and hence potentially reduce injury rates.

Based on the evidence in 2.5.4, 2.7 and 2.8 with the evidence in Study 1 (Ch 3). This chapter presents a controlled-trial to explore the biomechanical effects of a NMT programme among the Scottish female hockey players compared with a control group (who performed their usual warm up) on EMG, kinematic and kinetics factors that are associated with injury. We hypothesised that eight weeks of sport-specific neuromuscular training would: (1) increase muscle activity (primary outcome) before and after landing and in terms of time to peak muscle activity; (2) alter kinematic variables that were associated with injury (secondary outcomes); (3) reduce landing forces during a sagittal plane hop, hop and twist and an unanticipated sidecut task (tertiary outcomes); and finally (4) increase performance compared with controls who performed their usual warm-up (quaternary outcome).

5.1.1 Null hypothesis

There will be no difference in muscle activity, kinematics, kinetics and performance between the intervention group (after eight weeks of NMT) and the control group (after eight weeks of their usual warm up).

5.2 Method

A controlled-trial research design was used in this study. Each participant in the intervention group was tested prior to their first performance of the warm-up, which was then conducted three times per week for eight weeks (Steib et al., 2017). Then the players were re-tested. The control group participants were tested at baseline, after which they continued with their usual warm-up (see Study 2, Ch 4). Both groups were tested over a two-week period before the start of the experimental period and similarly after the eight-week intervention period. The intervention group performed the warm-up before both training sessions and matches.

5.2.1 Inclusion and exclusion criteria

The target group for this study were female hockey players who were at university. The inclusion criteria were that all participants must play hockey on a regular basis, be female and have been injury-free for the previous three months. They were also required to agree to undergo the test procedure before and after the intervention period.

There were two recruitment and testing periods: the first took place from September to December and the second from January to March to ensure that each participant undertook an unbroken experimental period. Those who were placed in the intervention group were required to be willing to perform the intervention rather than their normal warm-up.

According to a calculation performed by G*Power®, (Los Angeles, USA), in order to achieve 80% power and an alpha level of 0.05, a sample size of 20 players in each group was required (which was similar to the regime that was proposed by Donnelly et al., 1999). This sample size has been shown to detect a difference of 15% (SD of 15) (Zebis et al., 2016). Therefore, to account for any dropouts, we aimed to recruit 50 participants to this study, 25 to the control group and 25 to the intervention group (Figure 5.1).

5.2.2 Ethics

Ethical approval was granted by the institutional ethics committee before the commencement of data collection. Before the initial data collection session was undertaken, each participant was given a participant information sheet (Appendix 5.1) and the opportunity to ask questions. The guidelines that were to be implemented under the General Data Protection Regulation (GDPR) were explained. Each participant gave their signed consent to continue with the research (Appendix 5.1). Immediately before data collection, the process was reviewed and each participant completed a physical activity readiness questionnaire (PAR-Q) to assess their fitness to participate (Appendix 5.1).

5.2.3 Recruitment process

The recruitment and data collection was carried out between September 2015 and April 2017. In total, 43 young adult females were pre-tested after an initial recruitment of 49 (six did not attend the first session). Later, three who took part in the control (CON) group were lost to follow-up (dropped out) and further two CON participants were excluded during the data processing (as marker location was indecipherable and no data on 1 EMG sensor); one who took part in the intervention (INT) group was lost to follow-up due to injury, and one INT participant was excluded during data processing as marker location was indecipherable. The participant flow is presented in Figure 5.1, and participant information is shown in Table 5.1.

5.2.4 Tools and data collection protocol

The data were collected at the Biomechanics Laboratory of Edinburgh Napier University. Each assessment lasted for approximately two hours. Before each volunteer was tested, the motion analysis system was calibrated with the use of a 600mm machined Qualysis® calibration wand (Goteborg, Sweden), synchronised with the force platforms and EMG system. An error of only <1mm for each camera was acceptable. After completion of a consent form, all participants changed into Lycra shorts and a top. Height and body mass were measured (Quadra digital floor scale, SECA 808, Germany) and each player's leg dominance was established (defined by the leg with which each participant kicked a ball). The test procedure comprised three standardised tasks, which are detailed below.

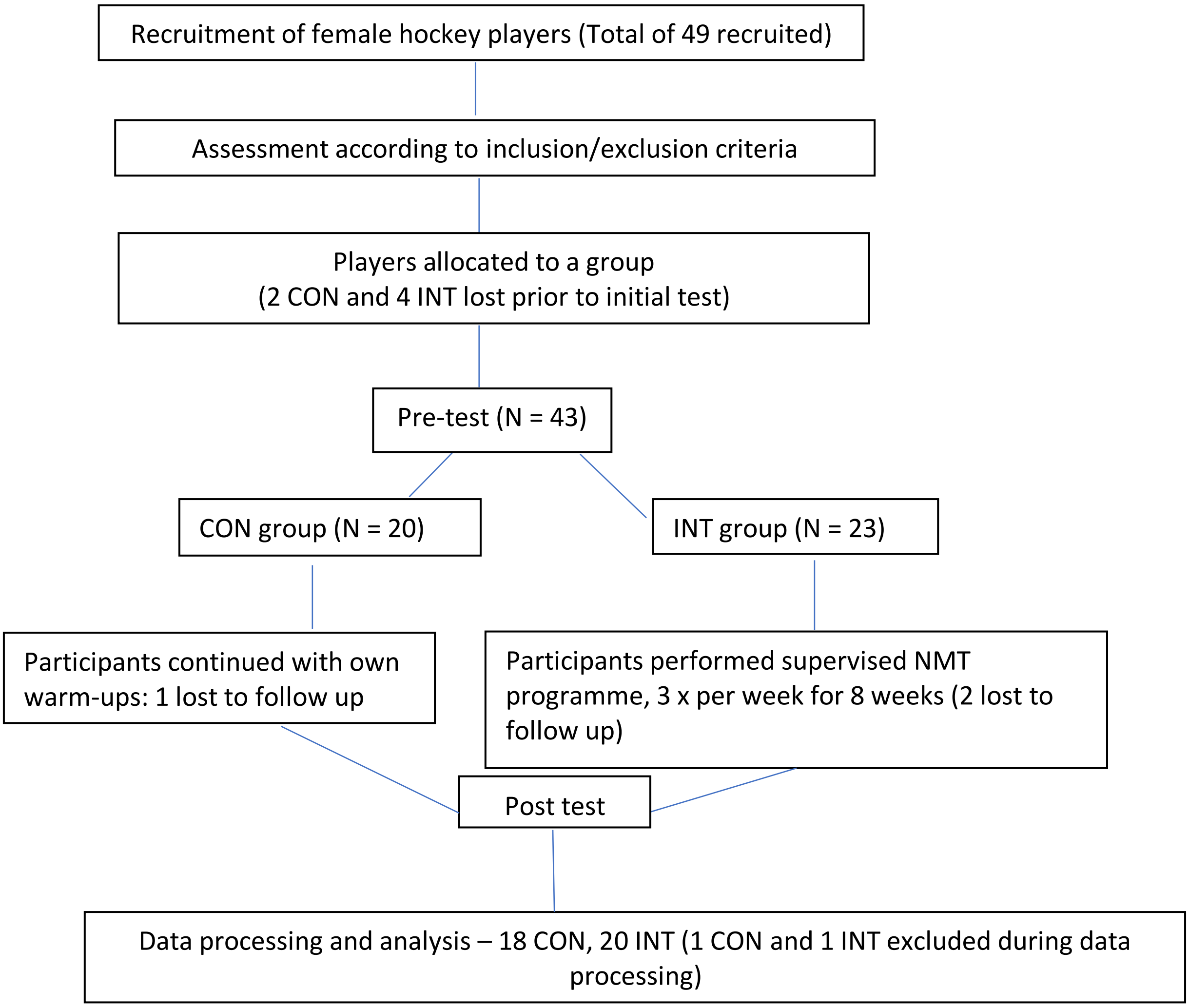

Figure 5. 1 Flow of participants through the study (CON = control group; INT = intervention group; NMT = neuromuscular training)

5.2.5 Test preparation and familiarisation

To prepare for the test, each participant cycled for three minutes at 60 rpm (two mins with 1kg of resistance on a Monarch exercise bike (Monark, Ergomedic 874E, Vanbro, Sweden), followed by one min with 1.5kg of resistance), and then they performed 10 squats and 10 lunges on each leg. After this, they undertook 2 x 10m accelerations and four run-and-cuts (two to each side – planned) as high intensity exercises and the latter similar to a test task. After this preparation, each participant rested for at least three minutes.

They then followed a familiarisation and practice routine for the three test activities. This routine consisted of a demonstration of each activity and the provision of standardised instructions (Appendix 5.9), after which they practised each activity at least five times (or as many times as was required) to become familiar with it. This was followed by another rest of at least three minutes. The EMG sensors were applied, followed by the reflective markers, and the motion capture calibration (static and dynamic) files were collected.

The EMG sensors comprised nine Delsys Trigno Wireless sensors (SP-W01D, Natick, Mass, USA) which sampled at 1925.925Hz (upsampled to 2000Hz) to measure muscle activity. Placement details are shown below. During the activities, each participant landed on a force plate (Kistler® Instruments, 9281CA Winterthur, Switzerland) that was sampled at 2000Hz. The data from the plate were fed into the master system, a Qualysis Tracker Manager (QTM)® (Version 2, Goteborg, Sweden), which sampled at 500Hz, and the motion was captured by 12 Oqus 300 motion-capture cameras.

The kinematic and kinetic data from the QTM® were subsequently exported to Visual 3D® version 6 (C-motion®, Germantown, USA). A pipeline was developed through which the variables were analysed. The variables are listed below. EMG data were exported to Delsys EMGWorks Analysis (Version 4, Natick, Mass., USA). All EMG data were processed by the root mean square (RMS) method with a 30ms window. All kinematic data was filtered using a 10Hz Butterworth bi-directional (4th order) filter following a residual analysis. A 20Hz Butterworth bi-directional (4th order) filter was used on the kinetic data. Statistical analysis was performed on the Statistical Package for the Social Sciences (SPSS) software package from IBM (v26).

5.2.6 Reflective marker and EMG sensor placements

The segments of the body were tracked to calculate kinematics that included the centre of mass. Therefore, 65 x 19mm retroreflective markers were placed on each participant as single markers on anatomical landmarks or as a cluster on segments (e.g. thighs) with double-sided adhesive tape. The trunk and feet were defined as a single segment (Appendix 5.4).

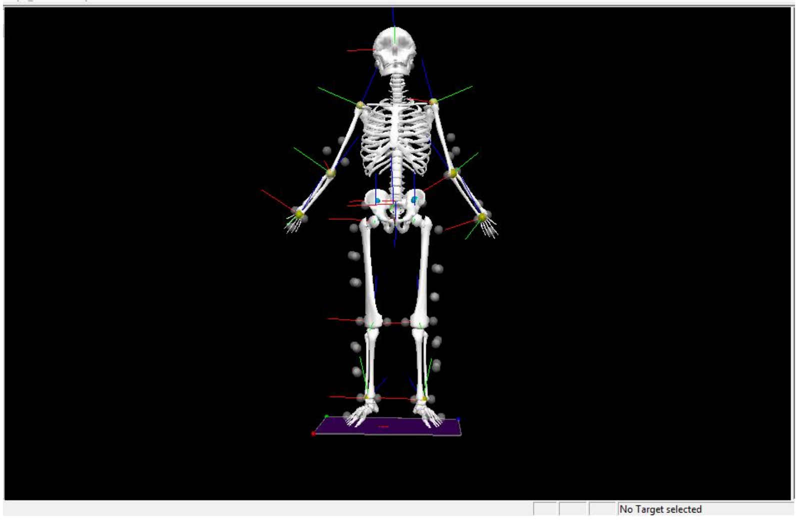

Figure 5. 2.1 Marker placement – anterior view (as seen by Visual 3D, C-Motion)

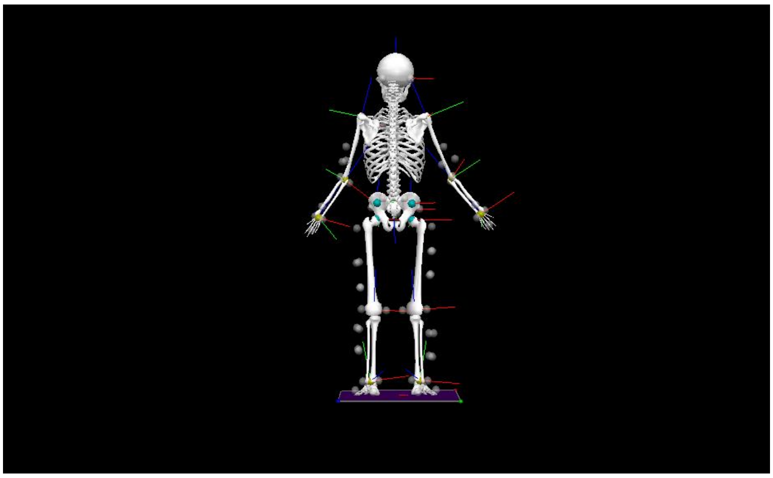

Figure 5. 2.2 Marker placement – posterior view (as seen by Visual 3D, C-Motion)

Wireless EMG sensors were placed on the dominant leg (defined as the preferred kicking foot) as dominant leg more likely to be injured (Hewett et al., 2010; Niu et al., 2011). Each sensor site was shaved and the site was wiped with an alcoholic wipe (to remove grease and perspiration) to aid adhesion (of the stickers attaching sensor to skin). The sensors were placed according to the recommendations of the European Union research project entitled surface electromyography for the non-invasive assessment of muscles (SENIAM) (1999) (Appendix 5.7). The sensors were placed on the muscle belly of the following muscles of the dominant leg: gluteus maximus, gluteus medius, rectus femoris, vastus lateralis, vastus medialis, semitendinosus, biceps femoris, gastrocnemius medius and gastrocnemius lateralis.

5.2.7 The movement tasks

The movements were selected to based ion the mechanisms of injury and the planes of movement that were frequent in hockey. As such, the sidecut is a mechanism which has been reported as frequent mechanism of injury more than other movements in hockey. Landing and frontal plane movements also are a frequently reported mechanism of injury and occur in hockey. Also, tasks that fit the above (i.e. valid for hockey players) and with clear parameters (reliability), elicit muscle activation (%normalised max) were chosen. The order in which the tasks (sagittal plane hop, hop and twist and unanticipated sidecut) were performed was selected at random by a number generator. Each participant had at least one minute's rest between each trial of the test task and three minutes between each task. Each task was repeated until five successful trials had been recorded.

5.2.8 Task 1 - Single-leg sagittal plane hurdle hop (dominant leg only)

The task was performed according to the protocol described by Struminger et al., 2013. Each participant was instructed to stand on the dominant foot only behind a line at a distance of 30% of their height from the centre of the force plate. A 10.16cm-tall hurdle was placed halfway between the participant's standing foot and the centre of the force plate. A metronome (Wittner, taktell, picollo, Germany) was set at 76 beats per minute (to standardise the speed). The participant was instructed to jump forward over the hurdle in the sagittal plane. The participant was required to clear the hurdle, land with the dominant foot on the force plate while the non-dominant foot remained in the air throughout the action. On the next beat of the metronome, the participant was required to jump backwards over the hurdle and return to the initial starting position, landing on the dominant leg. The action was performed in one continuous motion. Once landed, the participant was asked to return to the upright position as soon as possible.

The trial was deemed unsuccessful if the participant clipped or in any way touched the hurdle or hopped in a direction other than straight forwards/backwards; if the landing foot moved in some way to adjust for balance after contact; or if the non-dominant foot made contact with the ground before the trial was over. The trial was also classified as unsuccessful if either hop did not cover the correct distance, or if there was any excessive movement of the trunk or the non-dominant foot.

5.2.9 Task 2 – Single-leg hop with 180° twist on the dominant leg

The task was performed according to the protocol described by Struminger et al. (2013). The participants were instructed to stand on the force plate on their dominant foot with their non-dominant foot in the air in a balanced position. This would be in a self-selected position that was likely to be with the knee slightly flexed, the shank slightly posterior to the dominant leg shank and the foot slightly plantar flexed. The participant was then required to perform a hop of maximum possible height (as measured by the change in the height of centre of mass from standing to peak (Moir et al., 2016)) while performing a 180° turn in the transverse plane towards the non-dominant shoulder. The participant had to land with the same (dominant) foot on the force plate. The hop height was calculated during this task and was also the measure of performance.

Any pause in the initial hop phase (during loading and unloading) or movement of the hands from the designated position (by the body) led to the classification of the trial as unsuccessful. Transverse rotation was required to be 180° +/- 5°. Landing with a stutter step or foot movement on landing led to the assignment of an unsuccessful trial. Once landed, the participant could not pause or employ excessive arm (for example, arm circling), trunk or non-dominant leg movement to balance before returning to the upright position.

5.2.10 Task 3 - Unanticipated sidestep cut procedure

Participants were required to approach the force plate with a two-step run-up, land with the dominant foot on the force plate, cut 45 degrees to the direction of a light and accelerate through the timing gates at pace (Ford et al., 2005). Any sidestepping from the non-dominate side was discounted. The signal for the light was triggered once the participant had broken through the second gate (Smartspeed Pro, Fusion Sport, Australia), which was placed 50cm from the force plates. The land, cut and sprint were required to be performed at maximum pace (at least 7.714km/hr) (Figure 5.2).

Any sidestep cut that was performed outside the force-plate area was deemed an unsuccessful attempt at the task. Either a full or partial change of direction with the incorrect leg (to cut to the left the participant was required to push with the right leg, or to cut to the right, they had to push with the left leg) rendered the attempt void. The task had to be completed within the time constraint at a minimum of 7.704km/hr or 2.14m/s (to finish the task in 1.4s) from the second speed gate to the third speed gate. A 'crossover' cutting action (i.e., pivoting on the same leg as the direction of travel) was classed as unsuccessful. Finally, the participant was required to run between the timing gates. This method has been shown to have intraclass correlation coefficients of 0.88 or greater by Ford et al. (2005) who also found high R values for initial contact (R=0.93), maximum abduction (R=0.94) and maximum adduction (R=0.95) are reported to be over 0.8, which is considered acceptable for applied tests (Barrett, 2001).

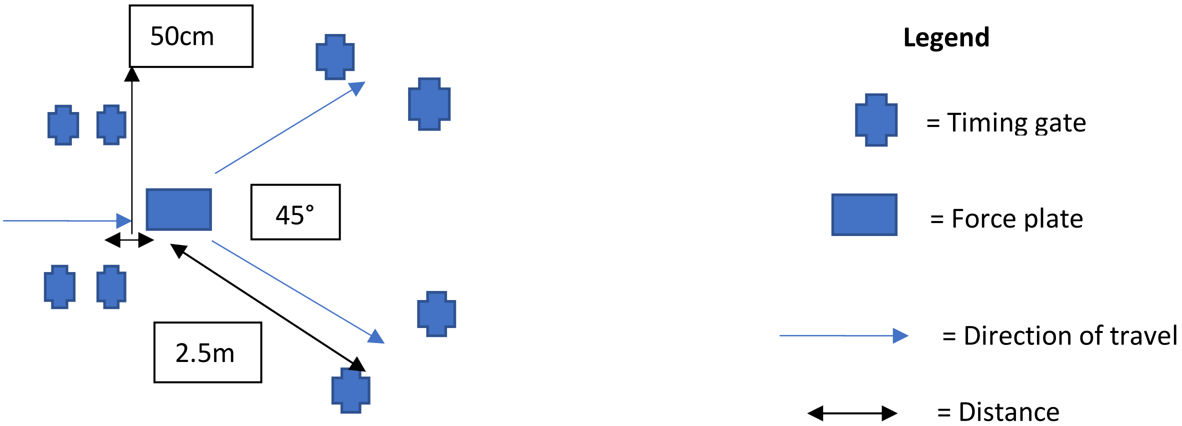

Figure 5. 2 The set up for the unanticipated cut task

During both the test and retest sessions at the beginning and end of the intervention period, each participant was given instructions on how to complete each task in the same way (Appendix 5.9) also testing only started when successful actions were demonstrated and the participant confirmed they were confident to complete the testing.

5.2.11 The Intervention and training period

The volunteer participants were allocated to a control or an intervention group. The control group members continued with their usual warm-up regime while those in the intervention group completed the hockey-specific NMT intervention, which was focused on balance, technique (especially during landing), muscle activation, core stability and sport-specific movements. Before the intervention period, 2 education sessions were completed for familiarisation (i.e., exercise were explained and participants performed each exercise once to show understanding but very limited or no training undertaken). Participants in the intervention group performed the hockey-specific NMT three times per week for eight weeks. The intervention contained activation and pulse raiser, mobility, core stability, lower extremity strength, plyometrics and sport-specific exercises. This was completed before matches and training sessions and was led by the primary investigator (TJ), who coached the participants through the intervention. The intervention Compliance, measured by the completion of each session, was recorded. The investigator coached each player through the exercises by use of external focus coaching points, for example, for landing; 'land like a butterfly' (Appendix 5.3).

Once the eight-week intervention had been completed, participants were re-tested within two weeks of the end of the intervention period. Before the re-test commenced, each participant completed an injury and physical-activity sheet in order to monitor any changes in these parameters that had occurred within the intervention period (see Appendix 5.8). The control group participants were tested, continued to perform their own warm-ups before both training and matches and play hockey for eight weeks, and were then re-tested.

5.2.12 Data reduction, filtering and normalisation

The mean of the five trials for each variable in the individual tasks for each participant was calculated. Individual variable means were collated to generate a pooled mean and standard deviation (SD) for the group in each context (pre/post-test) for comparison.

The EMG data was transferred for analysis to EMGWorks Analysis (Delsys, Natick, USA, version 4). The different EMG data-processing methods were considered in Chapter 2.12.9. Following an extensive literature review on the subject, the peak dynamic normalisation method has been chosen as appropriate (Albertus-kajee et al., 2011). Therefore, the EMG data were processed using the RMS with a 30ms window before normalisation to the peak EMG of that activity for each participant.

A residual analysis (Appendix 5.10) was performed for several different cut-off filter levels (i.e. 2, 4, 6, 8, 10, 12, 14Hz) on markers on the dominant leg, i.e. markers that were likely to be subject to the most artefacts in movement (Winter, 2005). This analysis showed that artefact differences reached a plateau at around 10Hz. Therefore, the kinematic data were filtered using a 10Hz Butterworth bi-directional filter (fourth order).

Force data in the literature have been filtered from 12Hz (Pappas et al., 2016) to 50Hz (Hewett et al., 2005), while a filter of 20Hz was used in other studies (Stafford, 2012) that included a similar test procedure to that of this study. Therefore, a filter of 20Hz was applied. The point of initial contact (IC) and peak force data would be affected if they were filtered at a higher frequency. The IC was determined to be at the point at which a vertical force of >20N was achieved. Pilot data indicated that this force was achieved after one frame, so the IC point was virtually unaffected. The axis interpretation for each joint in this study is described in Appendix 5.11.

5.2.13 Data processing

Consideration was given to outliers, since parametric statistical procedures are based on means and SDs. The presence of outliers can affect the power of the statistical test and even the type of test that is chosen (parametric / non-parametric tests). There are many ways to deal with outliers: keep them in, trim them (take them out), analyse with a robust method (bootstrapping), keep them in with a modified value using a mathematical formula or modify them to the nearest non-outlier value. This is called 'winsorisation' (Field, 2018). There are several versions; change the outlier to the nearest value that is not an outlier; or 5%, 10% or 20% winsorisation (which involves adjustment of the outer 5%, 10% or 20% of the data to the next nearest data point). This technique was developed by Charles Winsor in 1941. As discussed in Field (2018) (also by Guttman (1973) and Tukey, 1962), this technique can be applied to data points that lie more than three SDs outside the mean. In this study, only data points that were statistically extreme outliers were winsorised (Table 5.0) . Marginal outliers were not altered as they showed a negligible effect on the mean or the SD.

Table 5. 0 Winsorised data points

Group	Task	How many participants	Test	Body part	Plane/time point
CON	Sidecut	1	Pre	Trunk	X
INT	Sidecut	1	Post	VM	30ms prior to IC
CON	Sagittal plane hop	1	Post	VL	Time to peak
INT	Sagittal plane hop	1	Pre	Centre of gravity	Max knee flexion
INT	Hop and Twist	1	Pre	Ankle	X

5.2.14 Statistical analysis

Descriptive statistics were used to investigate data normality and outliers. Limited violations of normality and outliers were not treated but extreme outliers were corrected with winsorisation (Field, 2018). Although there were violations of normality in this data set, however, the data still fulfilled the criteria for the use of parametric statistical methods, i.e. normally distributed data, homogeneity and independence (Field, 2009; Thomas et al., 2011).

Inferential statistics in the form of a mixed-design analysis of variance (ANOVA) were used for the EMG data in SPSS® (IBM® SPSS®, 2015, v23) for each muscle separately. The analysis took into consideration the following factors: 1) between groups (CON, INT); 2) baseline and outcome measures (pre and post); and 3) the four different time points of EMG activity that were measured during the sagittal plane hop, hop and twist and sidecut (100ms before IC, 30ms before IC, 50ms after IC and at maximum knee flexion (MKF)). If this analysis returned any statistically significant main effects or interactions, a further mixed-design ANOVA was performed for each EMG time-point during the three tasks to identify the particular significant effects. A mixed-design ANOVA for each individual kinematic and kinetic variables was also applied. An alpha-level of <5% (two-tailed) was accepted as statistically significant in all analyses. Effect sizes (partial Eta^2) are reported as small (0.1), medium (0.3) and large (0.5) (Field, 2018).

5.3 Results

5.3.1 Introduction

This section details the participants' characteristics and compliance rates initially. Subsequently, the results from this study are presented in this section in order of outcome, therefore: EMG (primary outcome), kinematics (secondary outcome), kinetic (tertiary outcome) and the performance characteristics (quaternary outcome). The EMG data are presented for each activity and each group (control and intervention) for both the pre and post-tests (expressed as percentages of the normalised maximum including the SD). The kinematics for all variables and kinetic data are presented for all activities. All means, SDs and significant differences ($P \leq 0.05$, indicated with an asterisk) are indicated in Tables 5.2 and 5.3 for EMG and kinematic, kinetic and performance data respectively. Notable results are also detailed in this section. Additional statistical information is provided in Appendix 5.14.

5.3.2 Participant details

The summary of the participants in Study 3 are shown in Table 5.1 and in full in Appendix 2.12

Table 5.1 Study 3 participant details (mean, (SD) and p-values)

Group / Variable	**Control N = 18**	**Intervention N = 20**	**P - value**
Height (cm)	165.2 (4.7)	167.6 (5.4)	0.41
Body mass (kg) (before)	62.9 (7.8)	66.0 (6.3)	0.171
Body mass (kg) (after)	62.7 (7.8)	66.4 (6.4)	0.138
Difference (kg)	-0.2 (1.5)	+0.4 (1.2)	0.476
No. of games per week (n)	1.5 (0.6)	1.8 (0.4)	0.094
No. of training sessions (hockey) per week	1.2 (0.4)	1 0 (0.3)	0.914
No. of training sessions (not hockey)	1.0 (0.6)	1.1 (0.8)	0.421
Experience (yrs)	9.3 (3.1)	11.2 (2.4)	0.034*
No. of injuries during intervention period (n)	0.2 (0.4)	0.1 (0.3)	0.316

An independent samples T-test showed that there were no significant differences between the control and intervention groups except in the experience category. The intervention group had significantly more experience (t_{37}, -2.2, p = 0.034, confidence interval (CI) = -3.72 to -0.155).

5.3.3 Intervention group compliance

The rates of compliance of intervention group members were monitored regarding attendance at NMT sessions between the pre-and post-intervention tests (Figure 5.3). The mean compliance rate for intervention group was 66.9% (SD 15.4) and 81.5% (SD24.2) for the controls.

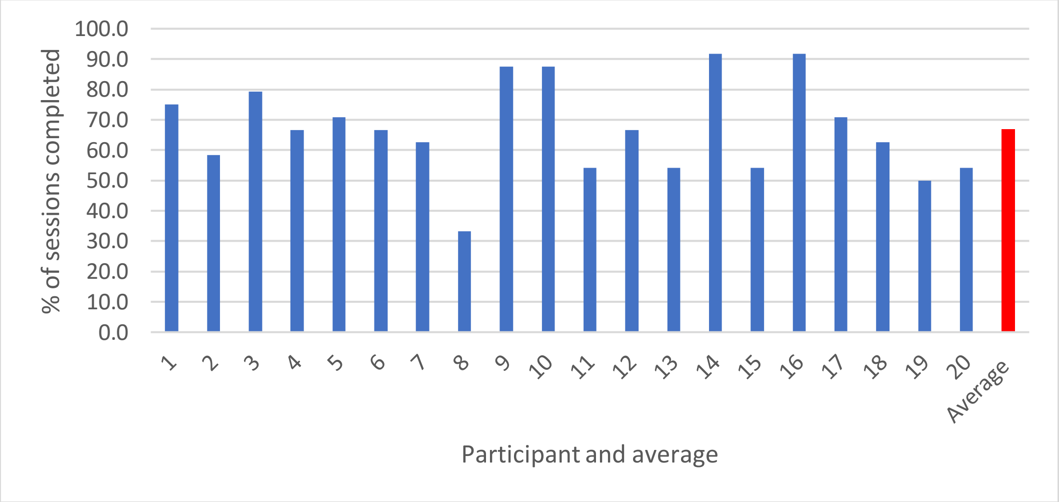

Figure 5. 3 Compliance of each intervention-group participant regarding attendance at training sessions (%)

5.3.4 Electromyography, kinematic and kinetic data

The pooled means for all muscles (% of normalised EMG and SD) for each of the time period and time to peak are in Table 5.2. The pooled means for kinematic, kinetic and performance data are in Table 5.3. The full results are detailed in Appendix 5.13

Table 5. 2 Normalised EMG data (%) and time to peak (s) for each muscle group in each activity (mean (SD))

Activity	**Sagittal plane hop (S)**					**Hop and twist (H)**					**Unanticipated cut (U)**				
Muscle Time point	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**
GASMED 100ms prior to IC	30.2 (16.1)	36.4 (17.2)	34.9 (17.8)	45.7 (14.7)	S^{a}	49.2 (15.9)	53.9 (16.5)	57.2 (20.5)	72.05 (12.7)	$H^{a,c}$	19.1 (13.3)	22.1 (13.6)	25.3 (12.6)	31.3 (11.4)	$U^{a,c}$
GASMED 30ms prior to IC	22.3 (10.1)	26.3 (13.6)	24.9 (13.6)	33.8 (11.7)	S^{a}	41.42 (24.9)	41.1 (21.2)	45.97 (19.2)	58.53 (15.8)		18.3 (11.6)	23.1 (16.7)	25.3 (14.9)	28.4 (11.9)	
GASMED IC to 50ms	22.5 (11.8)	25.3 (14.0)	24.6 (13.7)	26.2 (11.0)		33.4 (19.1)	33.5 (19.3)	38.4 (19.1)	43.1 (9.3)		19.9 (11.7)	20.2 (10.4)	25.0 (11.1)	28.8 (10.8)	
GASMED IC to MKF	37.6 (7.8)	41.9 (9.7)	41.3 (12.0)	47.7 (3.6)	S^{a}	33.1 (11.1)	33.1 (14.1)	33.9 (13.5)	44.0 (6.1)	$H^{a,b}$	42.1 (11.2)	46.4 (8.5)	45.1 (7.8)	53.1 (7.8)	U^{c}
GASMED Time to peak	-0.104 (0.002	-0.1103 (0.03)	-0.100 (0.02)	-0.007 (0.02)	S^{a}	0.122 (0.08)	-0.11 (0.06)	-0.117 (0.07)	-0.085 (0.07)		-0.123 (0.04)	-0.125 (0.03)	-0.112 (0.03)	-0.115 (0.03)	
GASLAT 100ms prior to IC	25.6 (11.7)	31.2 (16.1)	33.6 (19.8)	42.2 (14.6)	S^{a}	52.3 (15.1)	53.3 (16.3)	57.7 (18.7)	71.8 (13.1)	$H^{a,b,c}$	16.4 (10.1)	22.4 (13.7)	23.0 (11.04)	29.9 (12.3)	$U^{a,c}$
GASLAT 30ms prior to IC	20.9 (10)	26.1 (13.5)	27.33 (12.2)	28.8 (10.4)		43.8 (23.1)	46.4 (23.6)	50.4 (20.2)	59.9 (16.7)		17.9 (9.9)	24.0 (15.0)	27.1 (15.2)	25.9 (9.9)	
GASLAT IC to 50ms	19.7 (7.3)	23.3 (12.6)	24.8 (12.2)	25.5 (9.0)		35.5 (20.8)	39.3 (20.4)	38.0 (18.1)	46.1 (13.0)		18.7 (10.2)	20.8 (10.5)	24.1 (12.4)	28.3 (8.0)	U^{c}
GASLAT IC to MKF	37.7 (42.4)	42.4 (9.4)	41.8 (11.3)	49.0 (7.6)	$S^{a,}$ S^{c}	34.0 (14.1)	47.4 (9.5)	51.2 (9.2)	49.5 (9.5)	$H^{b,c}$	41.3 (11.3)	46.6 (8.1)	46.5 (10)	52.9 (7.8)	$U^{a,c}$
GASLAT Time to peak	-0.012 (0.02)	-0.109 (0.03)	-0.119 (0.02)	-0.112 (0.02)		-0.106 (0.08)	-0.103 (0.07)	0.09 (0.08)	-0.078 (0.07)		-0.12 (0.032)	-0.121 (0.028)	-0.122 (0.03)	-0.117 (0.03)	
HAMMED 100ms prior to IC	44.6 (14.4)	44.3 (22.0)	46.2 (16.8)	47.0 (12.7)		54.8 (16.0)	52.6 (16.9)	57.8 (16.1)	64.8 (9.9)		28.5 (7.1)	28.0 (12.9)	31.4 (13.0)	28.9 (8.8)	
HAMMED 30ms prior to IC	37.1 (14.0)	33.9 (19.4)	43.3 (17.3)	37.5 (13.2)		48.9 (20.5)	45.9 (16.6)	50.9 (19.7)	46.4 (15.3)		35.9 (11.5)	34.2 (18.6)	35.7 (15.1)	31.0 (9.9)	
HAMMED IC to 50ms	37.5 (14.6)	40.3 (13.3)	41.2 (12.9)	40.7 (11.7)		38.4 (12.8)	45.9 (16.6)	50.9 (19.7)	46.4 (15.3)		37.2 (11.6)	31.0 (8.3)	37.8 (11.5)	34.5 (9.8)	U^{a}
HAMMED IC to MKF	54.8 (8.2)	54.3 (6.4)	55.7 (6.1)	54.9 (7.2)		42.7 (8.1)	46.4 (11.5)	44.9 (11.8)	43.4 (7.5)		54.9 (11.8)	55.3 (11.8)	57.0 (10.6)	59.8 (9.0)	
HAMMED Time to peak	-0.131 (0.3)	-0.125 (0.02)	-0.134 (0.04)	-0.128 (0.4)		-0.175 (0.06)	-0.145 (0.06)	-0.158 (0.06)	-0.128 (0.08)		-0.132 (0.03)	-0.138 (0.4)	-0.134 (0.03)	-0.12 (0.03)	

Table 5.2 (contd.)

Activity	Sagittal plane hop (S)					Hop and twist (H)					Unanticipated cut (U)				
Muscle	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**
HAMLAT 100ms prior to IC	41.9 (15.6)	46.7 (21.1)	45.7 (18.7)	46.7 (10.8)		58.8 (10.3)	59.9 (13.4)	60.4 (13.0)	64.7 (11.1)		29.1 (10.2)	30.5 (17.0)	32.3 (9.9)	33.1 (11.3)	
HAMLAT 30ms prior to IC	33.0 (12.2)	39.6 (22.0)	40.9 (20.9)	39.1 (12.7)		59.3 (15.5)	60.1 (19.7)	59.0 (19.5)	65.4 (14.3)		29.1 (10.2)	30.5 (17.0)	32.3 (9.9)	33.1 (11.3)	
HAMLAT IC to 50ms	32.8 (11.4)	37.4 (14.5)	35.8 (10.8)	37.3 (10.2)		41.3 (12.4)	50.7 (21.1)	52.4 (18.5)	50.1 (14.8)		35.6 (11.1)	33.4 (9.9)	35.5 (12.2)	35.6 (9.6)	
HAMLAT IC to MKF	56.1 (10.3)	58.5 (5.9)	54.4 (7.6)	59.4 (4.8)	S^{a}	49.1 (10.3)	49.5 (8.5)	50.0 (11.4)	56.1 (8.0)		49.4 (13.0)	54.3 (10.7)	51.7 (10.0)	55.9 (7.5)	U^{a}
HAMLAT Time to peak	0.143 (0.02)	-0.135 (0.04)	-0.131 (0.04)	-0.133 (0.03)		-0.167 (0.05)	-0.157 (0.06)	-0.156 (0.07)	-0.145 (0.06)		-0.148 (0.04)	-0.139 (0.07)	-0.158 (0.06)	-0.116 (0.05)	U^{a}
VM 100ms prior to IC	67.5 (19.1)	63.5 (19.5)	66.9 (19.4)	73.9 (12.1)		62.1 (16.9)	58.3 (14.7)	57.0 (14.7)	59.4 (14.3)		31.8 (10.6)	36.9 (16.0)	43.6 (15.0)	50.1 (14.8)	$U^{a,c}$
VM 30ms prior to IC	48.6 (21.7)	45.4 (23.0)	50.4 (20.5)	55.34 (17.1)		63.4 (20.8)	64.7 (21.7)	65.9 (22.3)	66.5 (18.5)		29.8 (8.4)	34.8 (14.4)	36.9 (15.8)	40.6 (10.8)	
VM IC to 50ms	45.1 (17.4)	40.1 (13.6)	44.6 (13.4)	47.4 (13.3)		59.1 (19.2)	58.6 (22.5)	57.6 (22.3)	62.7 (20.1)		40.3 (10.9)	39.9 (11.9)	43.8 (12.6)	41.2 (13.6)	
VM IC to MKF	56.14 (10.3)	50.0 (9.5)	50.0 (7.8)	51.4 (9.2)	S^{b}	47.2 (10.4)	47.3 (12.2)	45.4 (13.3)	51.7 (10.5)		57.2 (9.2)	57.9 (8.2)	58.3 (8.6)	60.5 (6.3)	
VM Time to peak	0.025 (0.07)	-0.034 (0.07)	-0.037 (0.07)	-0.031 (0.05)		-0.689 (0.09)	-0.079 (0.06)	-0.076 (0.09)	-0.057 (0.06)		-0.123 (0.04)	-0.132 (0.4)	-0.111 (0.04)	-0.119 (0.03)	
VL 100ms prior to IC	54.3 (18.1)	52.53 (18.0)	52.0 (16.5)	60.9 (13.4)	S^{b}	63.0 (18.7)	63.7 (12.0)	61.2 (14.8)	64.3 (12.1)		30.2 (10.5)	29.7 (11.8)	41.4 (14.5)	39.8 (14.9)	U^{c}
VL 30ms prior to IC	42.8 (16.2)	41.1 (18.5)	43.0 (20.9)	44.8 (14.9)		63.1 (18.3)	66.7 (18.6)	64.6 (19.7)	70.4 (15.8)		32.1 (12.5)	31.5 (14.2)	40.6 (14.4)	36.1 (12.5)	
VL IC to 50ms	39.1 (13.4)	34.7 (12.8)	42.4 (14.8)	43.0 (17.6)		49.3 (17.6)	55.0 (19.1)	49.3 (17.3)	57.8 (14.2)	H^{a}	32.4 (13.9)	29.8 (10.6)	39.2 (15.9)	35.9 (12.6)	
VL IC to MKF	47.2 (7.4)	45.4 (7.6)	47.5 (9.5)	48.8 (7.3)		42.6 (6.9)	42.2 (9.8)	41.7 (11.2)	51.8 (10.0)	$H^{a,b}$	50.3 (11.5)	48.9 (5.8)	50.4 (14.8)	53.3 (8.0)	
VL Time to peak	-0.066 (0.06)	-0.796 (0.06)	-0.06 (0.07)	-0.049 (0.05)		-0.049 (0.1)	-0.067 (0.09)	-0.049 (0.08)	-0.055 (0.06)		-0.111 (0.03)	-0.115 (0.03)	-0.104 (0.05)	-0.093 (0.02)	

Table 5.2 (contd…)

Activity	**Sagittal plane hop (S)**					**Hop and twist (H)**					**Unanticipated cut (U)**				
Muscle	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**
RF 100ms prior to IC	55.2 (16.6)	48.6 (16.5)	47.8 (15.3)	54.6 (12.7)	S^b	60.3 (16.1)	54.5 (10.5)	50.7 (11.7)	55.8 (14.4)	H^b	29.6 (10.6)	28.0 (10.4)	32.7 (11.4)	35.1 (12.4)	
RF 30ms prior to IC	41.5 (16.5)	40.2 (15.4)	41.3 (16.3)	41.3 (16.3)		64.1 (18.4)	59.1 (17.2)	57.8 (18.5)	59.6 (17.0)		27.7 (10.2)	29.4 (10.6)	33.9 (15.4)	31.6 (13.6)	
RF IC to 50ms	38.9 (12.9)	35.5 (12.2)	43.2 (14.0)	42.6 (16.4)		49.7 (13.8)	52.6 (17.9)	51.2 (17.0)	51.2 (17.0)		35.1 (13.8)	32.4 (14.4)	38.0 (13.9)	36.1 (14.7)	
RF IC to MKF	44.5 (7.7)	44.3 (8.2)	44.3 (9.6)	46.7 (9.1)		40.6 (6.0)	43.3 (11.6)	43.5 (13.1)	45.0 (8.9)		49.4 (9.9)	49.2 (6.7)	51.0 (8.1)	54.6 (7.9)	
RF Time to peak	-0.059 (0.06)	-0.086 (0.05)	-0.07 (0.06)	-0.056 (0.06)	S^b	-0.05 (0.07)	-0.064 (0.08)	-0.07 (0.08)	-0.044 (0.06)		-0.118 (0.3)	-0.107 (0.2)	-0.1 (0.2)	-0.1 (0.3)	U^c
GMED 100ms prior to IC	26.5 (9.8)	29.7 (11.9)	32.7 (9.9)	35.5 (13.2)		55.7 (14.3)	55.9 (18.5)	53.5 (17.0)	55.1 (12.1)		23.2 (5.8)	19.7 (7.1)	25.7 (9.6)	22.3 (5.9)	U^a
GMED 30ms prior to IC	22.4 (10.1)	29.0 (10.8)	24.9 (13.6)	33.1 (9.0)	S^a	54.3 (18.3)	52.7 (18.7)	53.1 (18.9)	54.3 (16.3)		24.7 (7.1)	22.1 (8.4)	27.9 (11.7)	21.9 (6.1)	U^a
GMED IC to 50ms	39.6 (12.4)	33.8 (8.5)	37.4 (11.5)	38.7 (14.1)		50.1 (17.6)	52.8 (16.8)	58.2 (17.1)	58.8 (15.7)		18.9 (11.7)	22.1 (8.4)	25.0 (11.1)	22.0 (7.2)	
GMED IC to MKF	34.7 (5.7)	38.2 (8.0)	36.9 (7.9)	43.89 (8.9)	S^a	24.2 (11.8)	28.3 (13.0)	30.5 (12.8)	38.8 (9.3)	$H^{a,c}$	35.3 (5.2)	37.1 (7.8)	40.7 (9.8)	38.9 (7.8)	
GMED Time to peak	-0.123 (0.03)	-0.118 (0.03)	-0.114 (0.03)	-0.127 (0.03)		-0.131 (0.08)	-0.146 (0.05)	-0.141 (0.05)	-0.105 (0.06)		-0.126 (0.03)	-0.127 (0.03)	-0.122 (0.03)	-0.114 (0.02)	
GMAX 100ms prior to IC	36.2 (11.1)	34.1 (10.1)	34.5 (9.0)	37.5 (11.6)		54.6 (14.5)	56.0 (14.3)	51.3 (15.8)	52.5 (15.5)		22.3 (7.2)	21.9 (8.1)	27.2 (12.8)	25.5 (11.0)	
GMAX 30ms prior to IC	33.7 (12.7)	33.6 (12.7)	33.9 (9.5)	33.9 (14.9)		54.5 (17.9)	54.5 (18.8)	53.2 (19.1)	55.3 (20.1)		28.0 (9.8)	24.4 (9.6)	29.2 (12.6)	25.0 (12.0)	
GMAX IC to 50ms	28.8 (8.2)	25.0 (7.1)	25.7 (8.2)	32.2 (8.7)	S^b	55.3 (16.4)	56.2 (15.4)	54.8 (14.7)	61.4 (18.5)		19.9 (11.7)	20.5 (10.1)	25.0 (11.1)	29.0 (10.6)	U^c
GMAX IC to MKF	37.4 (6.4)	40.0 (8.6)	39.1 (6.9)	43.6 (11.3)	S^a	33.1 (11.1)	33.1 (14.1)	33.9 (13.5)	44.0 (6.1)		40.7 (8.4)	41.9 (6.9)	43.0 (10.0)	45.3 (18.9)	
GMAX Time to peak	-0.129 (0.04)	-0.116 (0.02)	-0.120 (0.02)	-0.109 (0.02)	S^a	0.143 (0.7)	-0.138 (0.05)	-0.121 (0.06)	-0.936 (0.05)	H^c	-0.139 (0.6)	-0.127 (0.04)	-0.131 (0.04)	-0.119 (0.02)	

CON = Control group; INT = Intervention group; IC = Initial contact; MKF – maximum knee flexion; GasMed = gastrocnemius medialis, GasLat = gastrocnemius lateralis, HamMed = semitendinosus, HamLat = biceps femoris, VM – vastus medialis; VL = vastus lateralis, RF = rectus femoris; GMed = gluteus medius; GMax = gluteus maximus; vGRF = vertical ground reaction force; RFD = rate of force development; Significant - ^{a} = time main effect, ^{b} = Time*group interaction effect, ^{c} = between group main effect, $p \leq 0.05$; IC = initial contact; MKF = maximum knee flexion; BW = body weight

Table 5. 3 Kinematic and kinetic results for each variable for each activity (mean (SD)) at initial contact

Activity	**Sagittal plane hop (S)**					**Hop and twist (H)**					**Unanticipated cut (U)**				
Variable	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**
Trunk flexion(°)	171.9 (6.4)	173.5 (6.7)	173.8 (3.6)	173.3 (5.5)		172.7 (5.2)	172.0 (4.5)	171.5 (4.7)	171.8 (5.3)		165.6 (5.5)	167.5 (5.6)	166.9 (6.0)	166.6 (7.6)	
Trunk lateral flexion (°)	-0.8 (3.3)	0.7 (4.7)	1.7 (4.8)	0.9 (4.1)		6.3 (4.0)	5.7 (4.5)	4.9 (4.2)	6.1 (3.9)		-1.4 (9.9)	-2.3 (5.2)	-1.8 (5.6)	-1.6 (3.5)	
Trunk axial rotation (°)	2.7 (4.8)	2.3 (5.5)	3.2 (3.6)	3.1 (4.0)		9.1 (8.2)	9.2 (6.5)	6.2 (7.6)	6.5 (7.3)		0.3 (2.6)	-0.4 (4.2)	-1.3 (4.3)	-0.8 (3.9)	
Hip Flexion (°)	34.4 (6.8)	33.3 (8.1)	32.8 (8.7)	28.5 (8.2)	S[a]	16.2 (4.9)	15.5 (5.9)	16.5 (6.8)	14.5 (6.7)	H[a]	38.9 (8.6)	37.9 (8.7)	42.0 (9.8)	35.8 (8.7)	
Hip Abduction (°)	-5.2 (4.2)	-5.4 (5.0)	-6.4 (4.4)	5.4 (4.5)		-4.2 (3.6)	-4.3 (4.6)	-4.33 (4.6)	-4.4 (4.4)		12.7 (5.4)	-10.9 (6.4)	-10.4 (4.9)	-9.7 (5.4)	
Hip axial Rotation (°)	8.4 (9.5)	3.5 (5.6)	4.9 (6.5)	3.9 (8.0)	S[a]	7.2 (9.9)	3.8 (7.4)	5.8 (5.5)	4.1 (6.93)		7.7 (8.8)	3.6 (5.4)	3.6 (6.6)	2.8 (8.1)	
Knee flexion (°)	-15.7 (4.5)	-15.6 (5.4)	-13.4 (5.7)	-13.0 (5.0)		-11.6 (4.3)	-12.7 (5.6)	-10.4 (4.9)	-10.5 (5.2)		-20.7 (6.7)	-18.6 (8.4)	-19.3 (10.1)	-18.0 (8.2)	
Knee adduction (°)	1.3 (4.8)	0.04 (4.2)	0.8 (2.8)	0.6 (2.9)		-2.9 (3.5)	-2.9 (3.5)	-2.2 (3.2)	-2.9 (3.5)		-0.3 (4.5)	-0.8 (4.9)	-1.0 (4.3)	-1.9 (3.1)	
Knee axial rotation (°)	-9.3 (6.9)	-6.6 (5.9)	-5.1 (7.4)	-6.5 (6.8)	S[b]	1.7 (9.5)	5.0 (7.5)	5.3 (6.4)	5.6 (7.4)		-2.22 (7.5)	0.08 (8.0)	1.8 (8.2)	0.4 (6.2)	
Ankle flexion (°)	39.7 (4.7)	41.9 (5.4)	41.9 (3.7)	41.9 (5.3)		45.7 (6.4)	48.0 (8.7)	49.6 (7.9)	50.4 (6.7)		69.8 (14.6)	73.0 (16.6)	67.9 (13.1)	64.3 (11.1)	
Ankle adduction (°)	-4.8 (4.6)	-3.7 (6.0)	-8.6 (5.6)	-7.1 (5.0)	S[c]	-7.3 (5.0)	-6.3 (6.9)	-8.7 (7.3)	-10.4 (7.9)		-11.0 (6.2)	-10.0 (6.5)	-10.5 (8.6)	-9.8 (5.7)	
Ankle inversion (°)	-15.4 (8.7)	-13.3 (6.6)	15.4 (6.8)	-16.0 (6.6)		-14.1 (6.7)	-11.7 (5.6)	12.8 (7.8)	-13.6 (6.9)		-20.3 (6.7)	-18.2 (6.7)	-22.1 (7.2)	-23.2 (8.0)	

Table 5. 4 Kinematic and kinetic results for each variable for each activity (mean (SD)) at maximum knee flexion

Activity	**Sagittal plane hop (S)**					**Hop and twist (H)**					**Unanticipated cut (U)**				
Variable	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**
Trunk Flexion (°)	163.2 (8.9)	164.2 (6.5)	167.6 (7.1)	168.6 (8.7)		171.2 (5.5)	172.3 (5.4)	172.6 (5.3)	172.0 (4.9)		148.4 (8.5)	149.7 (9.8)	153.0 (7.8)	151.9 (10.7)	
Trunk lateral flexion (°)	-12.0 (6.3)	-11.8 (6.8)	-11.6 (5.5)	-9.1 (5.8)		-15.5 (4.4)	-2.3 (5.1)	1.9 (4.7)	-2.1 (5.8)		-7.9 (4.4)	-10.5 (5.5)	-8.3 (5.9)	-7.9 (5.5)	
Max lateral flexion (°)	-13.4 (6.8)	-13.2 (6.6)	-13.2 (5.5)	-10.3 (4.2)		-2.4 (7.9)	-3.2 (7.2)	-3.3 (7.2)	-3.4 (7.3)		-11.4 (5.3)	-13.7 (5.1)	-11.6 (5.6)	-11.0 (5.0)	
Trunk axial rotation (°)	-2.5 (4.6)	-2.4 (7.2)	-0.5 (5.2)	0.1 (4.9)		6.1 (4.2)	5.7 (6.0)	5.4 (7.4)	4.5 (6.7)		-8.2 (5.4)	-8.5 (7.3)	-7.8 (4.9)	-8.3 (6.6)	
Lateral centre of gravity motion (m)	0.041 (0.007)	0.003 (0.008)	0.009 (0.008)	0.006 (0.009)		0.009 (0.02)	0.014 (0.01)	0.20 (0.02)	0.016 (0.019)		-0.056 (0.1)	-0.063 (0.02)	-0.056 (0.02)	-0.058 (0.017)	
Hip flexion (°)	48.46 (7.4)	33.3 (8.1)	45.69 (9.7)	28.47 (8.2)	S^{a}	36.18 (9.6)	34.96 (9.4)	34.1 (9.3)	34.9 (11.9)		45.7 (11.7)	46.1 (11.0)	45.2 (11.1)	38.8 (8.0)	U^{b}
Hip Abduction (°)	6.8 (4.0)	7.4 (3.2)	6.5 (3.6)	6.0 (4.2)		2.7 (5.6)	1.9 (3.6)	1.9 (3.6)	2.2 (5.1)		-13.0 (7.3)	12.4 (7.2)	-11.4 (6.6)	-10.4 (6.2)	
Hip axial rotation (°)	6.9 (8.7)	2.7 (5.0)	4.5 (6.8)	3.6 (6.6)		8.1 (9.7)	4.5 (7.3)	5.9 (7.0)	4.1 (6.3)	H^{a}	6.8 (7.7)	3.6 (5.4)	5.0 (6.6)	2.8 (8.1)	
Knee Flexion (°)	-58.3 (8.7)	-59.1 (6.8)	-54.9 (7.5)	-54.3 (6.6)	S^{c}	-44.3 (10.8)	-45.1 (10.1)	-41.2 (7.2)	-42.2 (10.1)		-61.8 (7.2)	-63.6 (6.9)	-62.0 (11.5)	-63.6 (6.8)	
Knee Adduction (°)	6.0 (6.4)	3.5 (5.9)	3.3 (6.3)	3.6 (5.1)		4.7 (4.9)	2.6 (5.3)	3.2 (5.8)	2.3 (5.1)	H^{b}	-1.1 (6.7)	3.7 (7.1)	-3.8 (7.6)	-5.7 (6.6)	U^{a}
Knee axial Rotation (°)	4.2 (6.0)	5.1 (6.5)	5.11 (6.5)	3.6 (5.4)		-0.8 (7.2)	2.5 (6.5)	0.7 (6.9)	-0.7 (7.8)		10.6 (5.2)	13.4 (6.4)	10.8 (7.6)	9.3 (6.2)	U^{b}
Max knee adduction (°)	-0.8 (2.0)	1.3 (1.0)	0.5 (1.7)	-0.4 (1.2)	$S^{a,b}$	0.4 (1.8)	0.7 (1.9)	0.7 (1.5)	-0.43 (1.8)		0.1 (2.67)	0.8 (1.8)	0.1 (1.7)	-0.4 (1.8)	$U^{a,b}$
Max knee abduction (°)	9.6 (3.6)	7.4 (3.1)	7.8 (3.3)	6.9 (2.0)	S^{a}	9.0 (2.8)	7.5 (2.8)	8.0 (2.5)	7.0 (1.8)	H^{a}	9.9 (3.5)	9.9 (3.2)	10.9 (2.8)	8.5 (2.8)	$U^{a,b}$
Max knee excursion (°)	8.8 (2.5)	8.5 (3.0)	8.4 (2.4)	6.3 (1.8)	$S^{a, c}$	9.3 (2.5)	7.9 (1.6)	8.4 (2.0)	6.7 (1.6)	H^{a}	10.1 (1.7)	11.3 (2.8)	10.8 (2.2)	8.0 (1.9)	$U^{a,b}$

Table 5.4 (contd.)

Activity	Sagittal plane hop (S)					Hop and twist (H)					Unanticipated cut (U)				
Variable	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**	**CON Pre**	**CON Post**	**INT Pre**	**INT Post**	**Sig**
Ankle flexion (°)	87.5 (6.5)	88. (4.3)	87.9 (5.0)	87.5 (4.7)		93.8 (6.7)	94.9 (5.2)	93.7 (6.2)	94.9 (5.2)		91.8 (8.6)	94.4 (6.2)	94.6 (7.6)	95.3 (5.4)	
Ankle abduction (°)	21.8 (6.5)	-20.1 (7.5)	-22.7 (9.5)	-23.6 (6.2)		-27.8 (6.5)	-24.5 (7.0)	-27.1 *(10.4)*	-25.9 (6.9)		-10.9 (6.1)	-10.9 (8.1)	-11.5 (6.9)	-12.2 (6.0)	
Ankle (°) inversion	-3.3 (4.7)	-1.7 (5.0)	-3.6 (4.9)	-4.6 (5.4)		-4.4 (3.8)	-3.7 (4.6)	-4.1 (3.3)	-5.0 (4.6)		-23.1 (6.9)	-21.3 (5.8)	-23.4 (5.8)	-24.3 (6.1)	
Peak vGRF (N)	1181.3 (222.6)	1487 (203.1)	1584.1 (178.1)	1562.7 (195)		1514.3 (249.8)	1520.0 (272.4)	1613.1 (260.9)	1495.0 (191.3)	$H^{a,b}$	1185.2 (212.6)	1226.3 (211.2)	1226.7 (208.6)	1171.5 (180.5)	
Normalised vGRF (BW's)	2.5 (0.19)	2.4 (0.3)	2.5 (0.2)	2.4 (0.3)		2.5 (0.32)	2.5 (0.42)	2.5 (0.375)	2.3 (0.3)	H^{a}	2.0 (0.3)	2.0 (0.3)	1.9 (0.3)	1.8 (0.2)	
RFD^{d} (BWs/s)	14.3 (2.9)	14.6 (2.7)	13.3 (1.5)	11.6 (2.3)	$S^{b,c}$	10.9 (1.2)	11.3 (1.5)	11.4 (2.0)	10.6 (1.1)	H^{b}	19.5 (9.9)	21.8 (9.4)	18.9 (9.1)	12.8 (5.71)	U^{b}
Hop Height (m)	N/A	N/A	N/A	N/A		0.17 (0.04)	0.17 (0.04)	0.16 (0.04)	0.16 (0.03)		N/A	N/A	N/A	N/A	

CON = Control group; INT = Intervention group; IC = Initial contact; MKF – maximum knee flexion; GasMed = gastrocnemius medialis, GasLat = gastrocnemius lateralis, HamMed = semitendinosus, HamLat = biceps femoris, VM – vastus medialis; VL = vastus lateralis, RF = rectus femoris; GMed = gluteus medius; GMax = gluteus maximus; vGRF = vertical ground reaction force; RFD = rate of force development; Significant - ^{a} = main effect, ^{b} = Time*group effect, ^{c} = between group, P≤0.05; ^{d} = mean rate of force development from IC to peak vGRF

5.4 Notable results

There were some significant differences within, between groups and a time*group interaction.

5.4.1 EMG

There were significant differences in the muscle activity 100ms prior to activity of the gastrocnemius medialis (Figure 5.4). In the sagittal plane hop, there was a significant within group effect (F(1,36) = 13.55, p = 0.001, r = 0.27) with a similar increase of activity in both groups. There was a within group effect and a between group effect in the hop and twist task and in the unanticipated sidecut (hop and twist: main effect – F(1,36) = 9.69, p = 0.004, r = 0.21; F(1,36) = 8.84, p = 0.005, r = 0.2; unanticipated sidecut: within groups effect - F(1,36) = 5.37, p = 0.03, r = 0.13; between-group effect – F(1,36) = 4.44, p = 0.04, r = 0.11). In both tasks, there were greater increases in the intervention group than in the control group. There were no significant differences at pre-test between the groups or significant interaction in these variables.

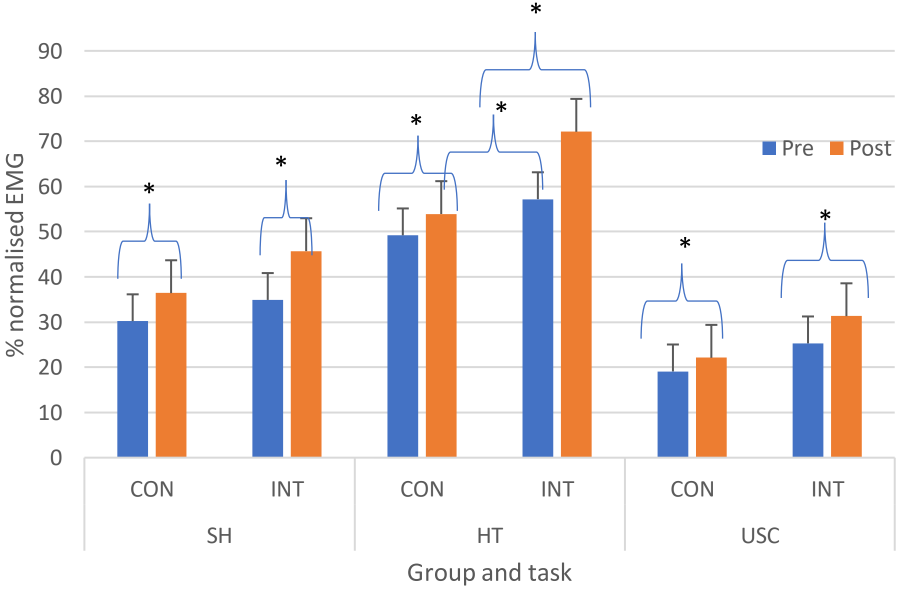

Figure 5. 4 Normalised EMG (%) for gastrocnemius medialis for all tasks and groups 100ms prior to landing (mean) (SD)

There was a significant within groups effect for the gastrocnemius medialis 30ms prior to landing during the sagittal plane hop (F(1,36) = 10.98, p = 0.002, r = 0.23). Also, during the sagittal plane hop, there was a significant within group effect for the gastrocnemius (medialis) from IC to MKF (F(1,36) = 12.25, p = 0.001, r = 0.25). In both cases, there were similar increases in both groups over time. There was a significant within group effect in the time-to-peak (F(1,36) = 4.49, p = 0.03, r = 0.12) with no significant between or time/group interaction as both groups decreased the time-to-peak by similar amounts. There was no significant difference between the groups at pre-test for both 30ms prior to landing and time to peak.

There was a significant within group effect (F(1,36) = 6.21, p = 0.02, r = 0.15) and a significant time*group interaction (F(1,36) = 6.14, p = 0.02, r = 0.15) for the gastrocnemius medialis during the hop and twist task, with an increase in activation in the intervention group and no change in the control group (Figure 5.5). Furthermore, there was a within group effect (F(1,36) = 10.3, p = 0.003, r = 0.22) and between group effect (F(1,35) = 5.1, p = 0.03, r = 0.12) during the unanticipated sidecut, with a similar increase in muscle activation in both groups. There were no significant differences at pre-test between the groups.

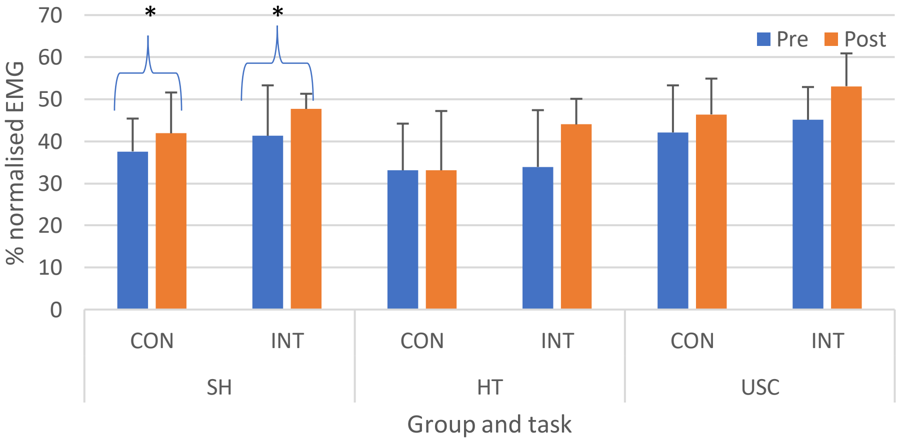

Figure 5. 5 Normalised EMG (%) for gastrocnemius medialis for all tasks and groups from initial contact to maximum knee flexion (mean) (SD)

There were some significant differences in the activity of the gastrocnemius lateralis 100ms prior to landing. There was a significant within group effect difference (F(1,36) = 16.6, p = 0.000, r = 0.32) during the sagittal plane hop, with significant within group and between group effect during the unanticipated sidecut (F(1,36) = 10.29, p = 0.003, r = 0.22; F(1,36) = 4.56, P = 0.04, r = 0.11 respectively). These showed similar increases for both groups. There was within group, between-group and time/interaction effects during the hop and twist (F(1,36) = 6.8, p = 0.013, r = 0.16; F(1,36) = 7.66, p = 0.009, r = 0.175; F(1,36) = 5.13, p = 0.03, r = 0.125) as the intervention group showed a 14% increase in activation with little change in the control group. There were no significant differences at pre-test between the groups.

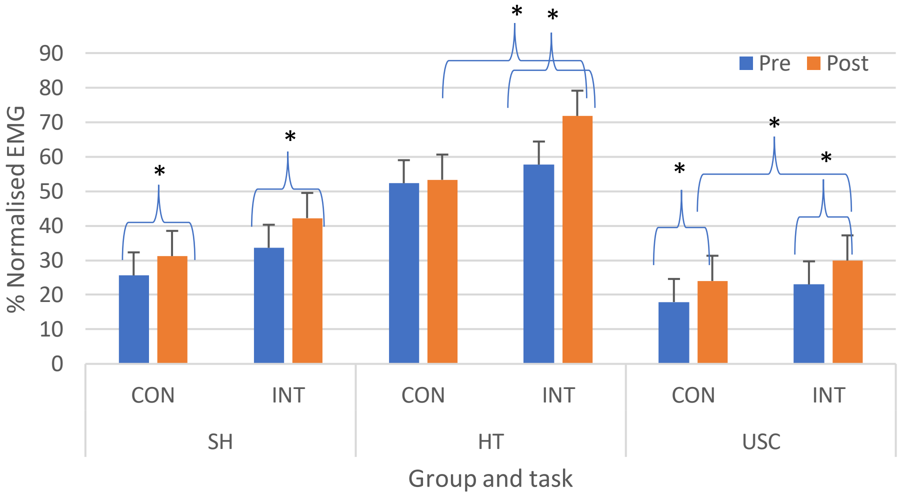

Figure 5. 6 Normalised EMG (%) for gastrocnemius lateralis for all tasks and groups 100ms prior to landing (mean) (SD)

There were significant within group and between group effects in the lateral gastrocnemius from IC to MKF during the sagittal plane hop and the unanticipated sidecut (sagittal plane hop, F(1,36) = 13.63, p = 0.001, r = 0.28; F(1,36) = 5.13, p = 0.03, r = 0.13; and unanticipated sidecut, F(1,36) = 6.0, p = 0.019, r = 0.14 and F(1,36) = 8.87, p = 0.005, r = 0.2 respectively) as there was a similar increase for both groups. There were significant between group and time*group interactions during the hop and twist (F(1,36) = 15.3, p = 0.000, r = 0.3; F(1,36) = 6.67, p = 0.004, r = 0.2 respectively) as the control group showed a large increase in muscle activation while the intervention group showed a small decrease. There was no significant difference in the pre-test results for the sagittal plane hop and unanticipated sidecut. There was however a significant difference between the pre-test results for the hop and twist (F(1, 36) = 20.43, p = 0.000, r = 0.36) with lower muscle activation in the control group.

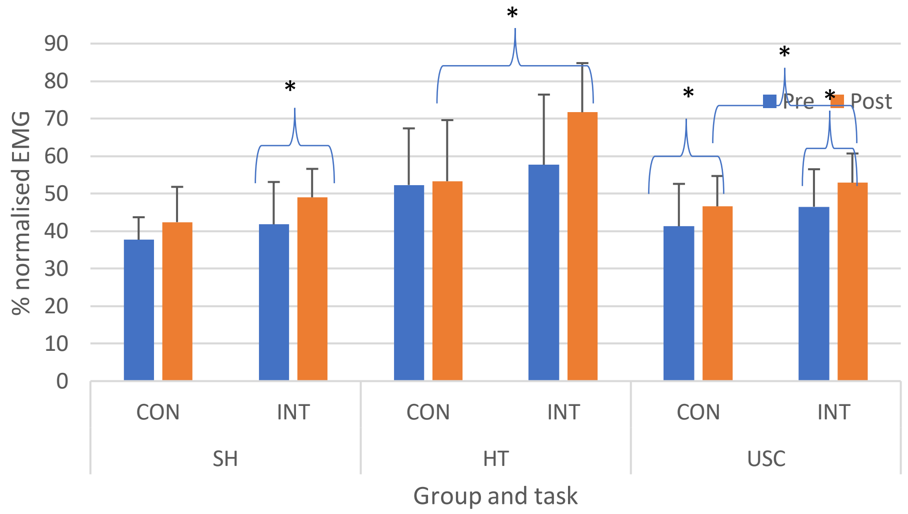

Figure 5. 7 Normalised EMG (%) for gastrocnemius lateralis for all tasks and groups from initial contact to maximum knee flexion (mean) (SD)

There were some significant differences in the quadriceps activity 100ms prior to landing. There was a significant time*group interaction difference in vastus lateralis and rectus femoris activity (F(1,36) = 4.24, p = 0.05, r = 0.016 and F(1,36) = 9.11, p = 0.005, r = 0.2 respectively) during the sagittal plane hop; the intervention group increased its muscle activation while the control group's activation slightly decreased in both cases. Also, there were significant within group and between group effects in the activity of the vastus medialis during the unanticipated sidecut (F(1,36) = 4.7, p = 0.04, r = 0.01 and F(1,36) = 0.9, p = 0.03, r = 0.03). Both groups exhibited similar increases, but the intervention group recorded higher activation levels at the pre-test.

After landing during the sagittal plane hop, there was a significant difference (time*group interaction) in vastus lateralis activity from IC to MKF (F(1,36) = 4.24, p = 0.05, r = 0.11) as the intervention group members increased their muscle activation while the control group members slightly decreased theirs. There was a within group effect and time*group interaction at the same time point during the hop and twist (F(1,36) = 7.39, p = 0.01, r = 0.17; F(1,36) = 8.36, p = 0.006, r = 0.19) as there was a 10% increase in muscle activation in the intervention group versus no change in the control group. There were also significant differences in the time-to-peak for the rectus femoris during the sagittal plane hop (time*group interaction) as the intervention group reached the peak earlier at post-test compared with the pre-test whereas the control peaked slightly later (F(1,36) = 4.15, P = 0.05, r = 0.1). There was a between-group effect for this variable for the unanticipated sidecut (F(1,36) = 0.41, P = 0.04, r = 0.12) as the intervention group members showed a greater decrease in their time-to-peak than the control group. There were no significant differences at pre-test between the groups for any of the quadricep variables.

There was a significant difference 30ms prior to landing in the gluteus medius activity during the sagittal plane hop (F(1,36) = 9.4, p = 0.004, r = 0.21) with a similar increase for both groups. There was also a significant within group effect for the gluteus medius during the sagittal plane hop from IC to MKF (p = 0.001) as the intervention group showed a larger increase than the controls. There was a significant within effect and between group difference during the hop and twist (F(1,36) = 15.4, p = 0.000, r = 0.3 and F(1,36) = 5.8, p = 0.021, r = 0.14) as there was a larger increase from pre- to post-test in the intervention group than the control. There were no significant differences at pre-test between the groups for both tasks and time points. There were no differences at the time point during the unanticipated sidecut.

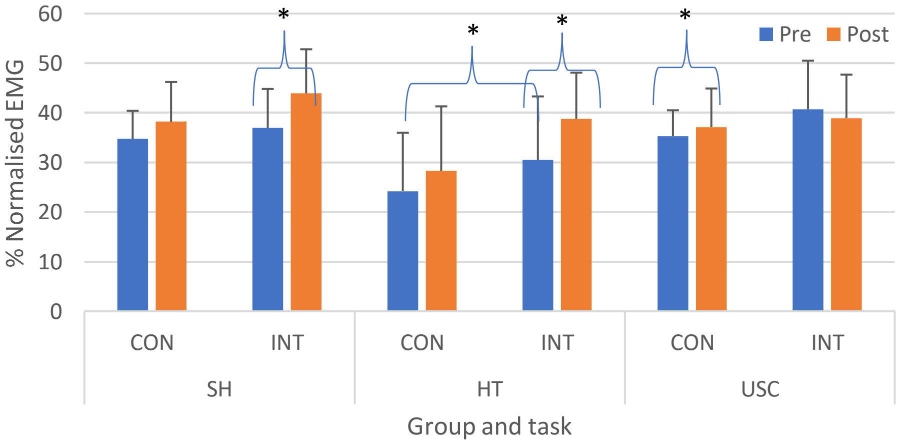

Figure 5. 8 Normalised EMG (%) for gastrocnemius medius for all tasks and groups from initial contact to maximum knee flexion (mean) (SD)

5.4.2 Kinematics

There was a significant within group effect and time*group interaction during the sagittal plane hop (F(1,36) = 4.4, p = 0.04, r = 0.11; F(1,36) = 29.2, p = 0.00, r = 0.45) as both groups decreased their knee abduction, by a slightly greater amount in the control group in both cases. There were also significant within group effects during the sagittal plane hop and hop and twist (F(1,36) = 7.0, P = 0.01, r = 0.16; F(1,36) = 6.58, P = 0.02, r = 0.15, respectively). There was also a within group effect and a time*group interaction during the unanticipated sidecut (F(1,36) = 7.6, p = 0.009, r = 0.18 and F(1,36) = 49.6, p = 0.00, r = 0.58, respectively) as there was a decrease in the intervention group with no change in the control group. There were no significant differences between the groups at pre-test.

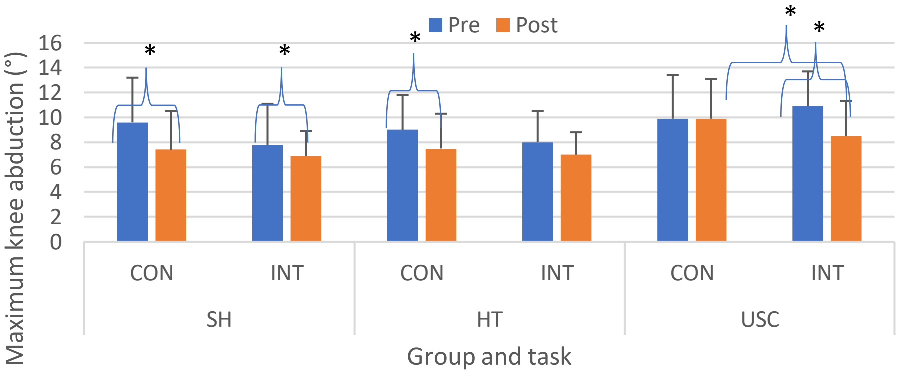

Figure 5. 9 Maximum knee abduction for all tasks and groups (mean) (SD)

There were significant within group and between group effects for knee excursion during the sagittal plane hop, a within group effect and a time*group interaction for the unanticipated sidecut, and a within group effect for the hop and twist (F(1,36) = 6.0, p = 0.02, r = 0.14; F(1,36) = 4.6, p = 0.04, r = 0.11; F(1,36) = 7.2, p = 0.01, r = 0.17; F(1,36) = 49.6, p = 0.000, r = 0.6; F(1,36) = 25.6, p = 0.000, r = 0.42, respectively). In all three tasks, knee excursion decreased in the intervention group from pre- to post-test with very similar results in each test in the control group. There were no significant differences between the groups at pre-test.

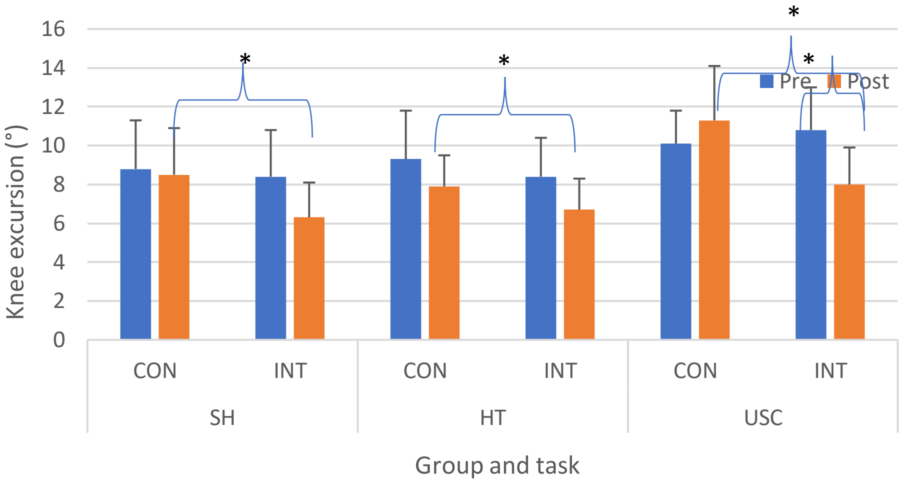

Figure 5. 10 Knee excursion for all tasks and groups (mean) (SD)

5.4.3 Kinetics

There were some significant differences in the rate of force development (RFD) across time and between the groups; in each task, the RFD was slightly increased in the control group, whereas there was a decrease in the intervention group, especially during the unanticipated sidecut. There was a significant time*group interaction and between group effect during the sagittal plane hop (F(1,36) = 4.3, p = 0. 045, r = 0.11; F(1,36) = 10.4, p = 0.003, r = 0.23, respectively). There was a significant time*group interaction for the hop and twist and for the unanticipated sidecut (F(1,36) = 9.3, p = 0.004, r = 0.21; F(1,36) = 11.5, p = 0.002, r = 0.24, respectively). There were no significant differences between the groups at pre-test.

There was also a significant within group effect and time*group interaction in peak vertical ground reaction force (vGRF) and a within group effect for normalised vGRF for the hop and twist task (F(1,36) = 4.73, p = 0.04, r = 0.12; F(1,36) = 3.7, p = 0.02, r = 0.14; F(1,36) = 4.8, p = 0.04, r = 0.12, respectively). There was a decrease in the peak vGRF in the intervention group, whereas the control group showed a similar result from pre- to post-test. There were no significant differences between the groups at pre-test.

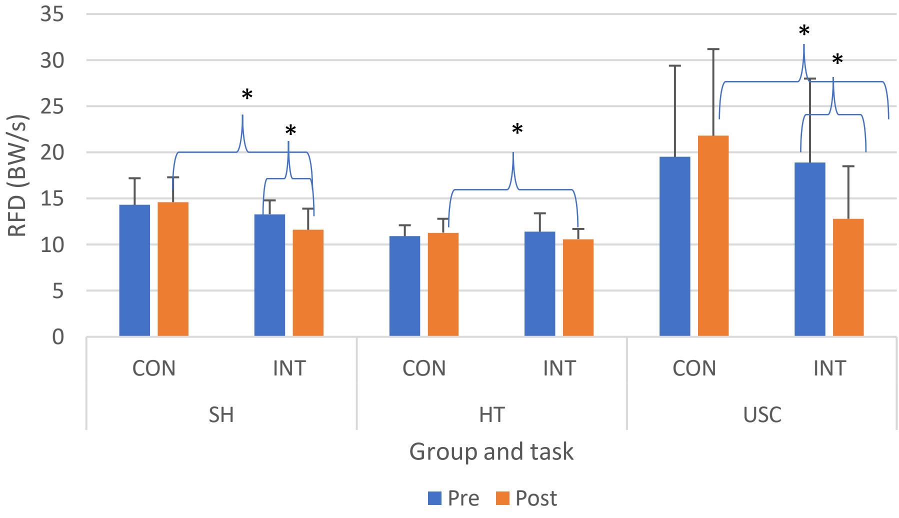

Figure 5. 11 Rate of force development for all tasks and groups (mean) (SD)

5.4.4 Performance

The results of the performance task (see 2.8.7) showed that each group produced the same hop height of 0.15m during the hop and twist. The results showed that there were no significant differences in performance between the control and intervention groups.

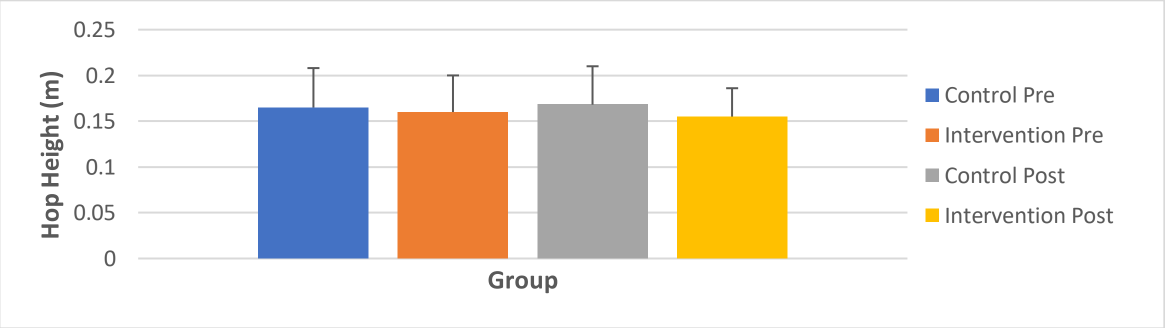

Figure 5. 12 Performance during hop and twist (mean) (SD)

5.4.5 Variability

Variability was calculated for the EMG, kinematic and kinetic variables (as set out by Stergiou and Decker, 2011) with a %CV ratio of <0.87 is less variability, 0.87-1.15 equals a trivial change and >1.15 equals a substantial increase (Drinkwater et al., 2008). A difference of 0.1 has been deemed a substantial difference (Legg et al., 2017). Therefore, the intervention group were less variable (a substantial difference for EMG and kinematics) following 8 weeks of NMT than the control group performing their usual warm up.

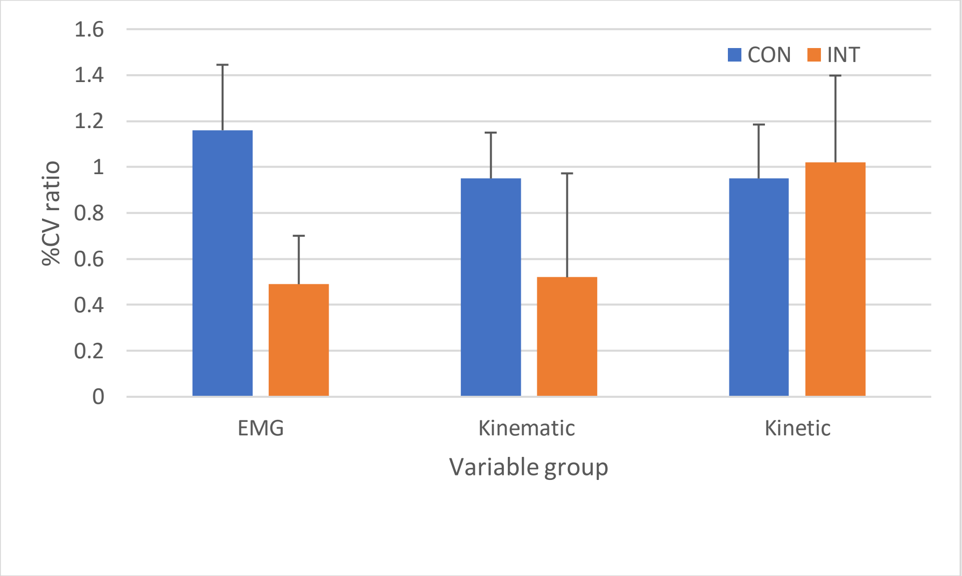

Figure 5.13 %CV ratio for the EMG, kinematic and kinetic variables (%CV ratio, SD)

5.4.6 Summary of results

Although the majority of the variables, including performance, showed no differences after eight weeks of either NMT or the participants' 'normal' warm-ups. There were, however, some significant differences in the muscle activation, kinematics and kinetics results that indicated the effects of NMT. There was a significant between-group differences in the gastrocnemius medialis muscle 100ms prior to landing in the sagittal plane hop and hop and twist as well as significant time-group interaction for hop and twist and unanticipated sidecut for this muscle and time point. Also, significant time-group interaction for this muscle from initial contact to maximum knee flexion. There was a significant between group effect for the gastrocnemius lateralis for the hop and twist 100ms prior to initial contact as well as for all three tasks from initial contact to maximum knee flexion. Also at this time point, there was a significant time-group interaction in the hop and twist. There was a time-group interaction for vastus lateralis and rectus femoris 100ms prior to landing and time-group interaction for vastus lateralis from initial contact to maximum knee flexion in the sagittal plane hop and a between group effect for the vastus medialis at this time point as well and a time-group interaction. Finally, there was a significant between group effect for the gluteus medius 30ms prior to landing in the hop and twist.

There was notable reductions in knee abduction in the control group in the Sagittal plane hop and hop and twist. The intervention group exhibited significantly reduced knee abduction and knee excursion as a significant time-group interaction was observed in the sagittal plane hop and unanticipated sidecut for knee abduction and a time-group effect for the unanticipated sidecut. Furthermore, the intervention group had significantly decreased RFD (a between-group effect and inter-group interaction) during the sagittal plane hop with a time group effect for the hop and twist and unanticipated sidecut.

5.6 Discussion

5.6.1 Introduction

The NMT intervention was designed to reduce the occurrence of risk factors associated with non-contact injuries (which were reported in Chapter 3) and to improve upon the current practice (reported in Chapter 4). Furthermore, this study is the first, to date, to explore the biomechanical effects of an NMT programme on female recreational hockey players. The design of the intervention was informed by previous studies (Hewett et al., 1999; Myklebust et al., 2003; Myklebust et al., 2003; Soligard et al., 2008; Swanik et al., 1997), systematic reviews and meta-analyses (Leppanen et al., 2014; Sugimoto et al., 2012; 2015). Therefore, the aims of this study, which were successfully addressed were to: (1) assess muscle activity (primary outcome) following neuromuscular training before and after landing and its time-to-peak; (2) alter kinematic variables that are associated with injury (secondary outcomes); (3) reduce landing forces during the sagittal plane hop, hop and twist and unanticipated sidecut tasks (tertiary outcomes); and finally (4) to increase performance compared with controls who performed their usual warm-up (quaternary outcome).

This discussion will consider the key variables for all the activities together. It will focus initially on the EMG (primary outcome) results for each task, and then on the kinematic data (secondary outcome). The discussion will conclude with considerations of the kinetic (tertiary outcome) and performance data (quaternary outcome). This section will also consider the participants’ compliance rates, the programme’s implementation and the limitations of the study.

5.6.2 EMG

There were some muscle activation changes in both the control and the intervention groups. There also were some significantly greater increases in the intervention group following the NMT programme.

5.6.3 Gastrocnemius

There was significantly greater activation of the gastrocnemius (medialis (GasMed) and lateralis (GasLat)) in the intervention group both prior to and post landing. There was a greater increase in activation of these muscles in the intervention group compared with the control group 100ms before landing in all three tasks (GasMed – sagittal plane hop (S) = +4.6%, hop and twist (H) = +11.2% and unanticipated sidecut (USC) = +3%; GasLat – S = +3%, H = +13.1%, USC = +0.9%). There was greater activation of the gastrocnemius medialis after landing (IC to MKF) in the intervention group in all three tasks and greater activation of the gastrocnemius lateralis in two of the three tasks (sagittal plane hop and unanticipated sidecut). This increased muscle activation could have developed through the dorsiflexion exercises that were undertaken in the first phase of the intervention, the plyometric, agility and simulated game sections. These exercises can improve reactivity (Lephart et al., 2005; Wilderman et al., 2009). As Bencke et al. (2018) explain, these exercises involve rapid foot movements and changes of direction. Therefore, during the intervention, the gastrocnemius underwent considerable loading and unloading and this may have led to the development of a quicker reaction to IC. This development may not have been possible in the control group, the members of which may not have performed agility exercises in their warm-ups. This may explain the differences between the groups.

The gastrocnemius appears to have distinct functions. The first is to stabilise the knee joint and reduce the strain on the ACL (Fleming et al., 2001); the greater the tension in the muscle surrounding the knee, the greater the stiffness and stability (Morgan et al., 2014), particularly in the lateral portion of this muscle (Wolf et al., 1998). Electrical stimulation models have indicated that gastrocnemius can improve resistance to anterior tibial displacement. Therefore, greater activation may provide greater protection against injury. Its role, however, does appear to depend on the knee flexion angle. At low knee flexion angles, this muscle may increase ACL strain (Fleming et al., 2001). However, there appears to be evidence both to support and to contradict this finding (Mokhtarzadeh et al., 2013).

The stability of the ankle joint, with other muscles, is dependent on the muscular activity of the tibialis anterior, peroneus longus, and the gastrocnemius lateralis and medialis (Wolf et al., 1998). Muscle activation in the ankle helps to provide stability, especially with activation of the gastrocnemius medialis (Błaszczyszyn et al., 2019). Also, the medial gastrocnemius has been shown to be ‘programmed’ to be activated before landing to stiffen (decreasing the downward displacement of the centre of mass) the ankle and knee joint on landing. Activation of the gastrocnemius lateralis also performs this task, and the gastrocnemius lateralis contributes to leg stiffness (Kuitunen et al., 2011) reducing the risk of ankle and knee injury.

5.6.4 Hamstring

There were no significant time/group interactions in either the biceps femoris or the semitendinosus. This was despite the inclusion of agility and plyometric exercises in the intervention that were similar to those introduced by Lephart et al. (2005). Moreover, this intervention included eccentric loading exercises (arabesque and Nordic hamstring exercises). Other interventions also have seen a non-significant increase in hamstring activity (Zebis et al., 2015). However, there was a significant decrease in the hamstring activity in the control group and along with an increase in the quadriceps activity significantly altered the hamstring:quadricep ratio which is important in knee injuries (Opar et al., 2014). There was mixed results report by Weir et al. (2019) with non-significant changes in muscle activation however, these changes altered pre-contact co-contraction ratios to be more medially directed after intensive training. This change was observed in the weight acceptance phase after intensive training but returned to a lateral co-contraction direction in the maintenance phase.

The result in this study may due to the protocol that was implemented. The intervention implemented by (Mjølsnes et al., 2004) contained a longer intervention period (10 weeks), more repetitions, progressions and with a greater compliance rate (96%) than this study (67%). Compliance also may be a key factor as Ishøi et al. (2018) implemented the same protocol as Mjølsnes et al. but had a lower compliance rate (60%) and had a smaller improvement. However, there have been positive changes after just six weeks (Cuthbert et al., 2020). Furthermore, Cuthbert et al. (2020) suggest that enhanced technique is more desirable than the amount of work. Also, it may be that the quality and effort during the movement was a factor in this study during the hamstring exercises as Weir et al. (2019) reported high commitment and motivation. A more progressive approach could be adopted with a longer intervention period.

This study measured muscle activation rather than injury rates or strength as others have reported (Van Dyk et al., 2019). Therefore, the intervention may, if measured, have altered these variables. Furthermore, the data process method may mask any changes as the EMG data was normalised to the peak during the activity rather than an absolute value. Moreover, the inter-trial variability and measurement error may be sufficient to elicit a non-significant result. The co-efficient of variation showed that the intervention group demonstrated less variability (a ‘substantial’ change (Drinkwater et al., 2008) following NMT than the control group did performing their usual warm up (global mean – Intervention group = 0.68; control group 1.12), a substantial difference (Legg et al., 2017).

Activity of the hamstring muscles, especially the semitendinosus, has been reported to be a key factor in reducing the number of ACL injuries. Increased semitendinosus activity reduces knee abduction and external knee rotation (Zebis et al., 2008), reducing the strain on the ACL. This is pertinent since ACL-injured athletes (especially females) have been found to show greater knee abduction at IC than their uninjured counterparts (Hewett et al., 2005). To compound this, female team sport players have been shown to exhibit significantly reduced pre-landing semitendinosus activity following 12 weeks of usual training. However, wobble board and balance training has been shown to increase semitendinosus activity and to significantly decrease vastus lateralis activity, which produced a combined highly significant intervention-control difference (Zebis et al., 2016). Furthermore, Zebis et al. (2008) found a significant increase (10%) in semitendinosus activity post landing with exercises including a weighted single leg deadlift similar to the arabesque in this study. However, Zebis et al. (2015) included more repetitions of this exercise than in this study. This was also found by Letafatkar et al. (2019). Therefore, NMT can reduce the anterior-posterior imbalance that is often found in females (Zebis et al., 2009). These alterations in muscle activation can reduce the anterior tibial translation (ATT), which can place the ACL under greater strain especially at low knee flexion angles (30-45°) (Fleming et al., 2001), and can reduce external knee flexion, knee abduction and tibial rotation moments that also increase the strain on the ACL, particularly in the first 50ms post-landing (Bencke et al., 2013; Kristianslund & Krosshaug, 2013)

Furthermore, Zebis et al. (2008; 2015) reported a decrease in lateral muscle activation (biceps femoris and vastus lateralis) following NMT. Therefore, the performance of NMT may reduce the medial-lateral imbalances, which may help to reduce knee abduction and external tibial rotation. Greater medial activity may reduce knee abduction, which significantly contributes to ACL injuries (Hewett et al., 2005).

An increase in contraction of the hamstring (and of the gastrocnemius) can counter strain on the ACL. This is more effective with a 15° knee-flexion angle or greater (Mesafar and Shirazi-Adl, 2006) as the line of pull acts posteriorly on the tibia. Further, the increase in hamstring tension, via accentuated hip flexion, may also limit peak ACL strain (Withrow et al., 2006).

5.6.5 Quadriceps

There were some significant differences in the activation of the muscles of the quadriceps, both prior to IC (vastus medialis and lateralis) and post landing (rectus femoris), with significantly greater activation in the intervention group (Table 5.2). The increase in activation may have been caused by the strength (squats and lunges) and power-based activities (plyometrics and sprints) that were introduced in the intervention. Females have been observed to contract their quadriceps to stabilise the knee joint to a greater extent than males (Hewett et al., 1996). This increase in activity could potentially exacerbate an existing problem with female athletes. Further to potential ATT (anterior tibial translation), via the inferior patella tendon and the subsequent additional ACL strain, increased quadriceps activity (especially with no corresponding hamstring activation) could increase the use of the ‘quadriceps-dominant’ and ‘ligament-dominant’ landing strategy (Hewett et al., 2010). This strategy involves reliance on the ligaments, joint structure and articular cartilage rather than the muscular system to absorb GRFs. Performance of posterior chain exercises, such as plyometrics and concentric and the aforementioned eccentric Nordic hamstring exercises, can counter this problem (Hewett et al., 2010).

Quadriceps activity resists the internal knee extension moment that counters the external knee flexion moment during landing (Shimokochi et al., 2016). Increased quadriceps activity (through eccentric muscle contractions) could significantly reduce the loading rate and peak vGRF and enable greater knee flexion in the sagittal plane (Huang et al., 2020; Nagai et al., 2013). A debate continues regarding the effect of sagittal plane mechanics on ACL injury (McLean et al., 2004) and the effect of the occurrence of peak vGRF, quadriceps force and anterior tibial force all at significantly different times (Ueno et al., 2017). Although stabilisation of the knee and attenuation of landing forces are important, there is considerable concern about the effect of increasing the quadriceps activity, as was the case at some points in this study, on ACL injury, especially if the quadriceps force increase is combined with knee abduction and does not involve a correspondingly increased hamstring activity (Kiapour et al., 2014; Quatman and Hewett, 2009; Withrow et al., 2006) as this will negatively impact the hamstring:quadricep ratio.

5.6.6 Gluteals

There were some significant differences in the gluteal activity between pre- and post-test. The trend in the results suggests greater activity at post-test with a slightly greater increase for the intervention group. There was significantly greater medius activity post landing (IC to MKF). The additional increase in the intervention group may have been because lower limb strength may have improved through the application of squat, front and lateral step and lunges, core stability section and the plyometric exercises in the intervention (Kopper et al., 2012; Reiman et al., 2012). Furthermore, there was targeted gluteus medius activation during hip abduction particularly in the mobility, core stability and the lateral movements in the strength, plyometric and sports specific movements. Furthermore, there was corrective feedback to encourage hip and knee adduction.

The increase observed (notably GMed = +4.2% at IC to MKF and GMax = +6.1% from IC to MKF during the hop and twist; +3.4% from IC to 50ms during the unanticipated sidecut) was not as large as those found by Weir et al. (2019), who reported a significant increase in gluteal activity (30%) as part of total muscle activity during the weight-acceptance phase of a sidecut manoeuvre after nine weeks of NMT. Weir et al. also reported there was, however, a slight reduction in activity during the period from week nine to week 25. This coincided with a reduction in the frequency of NMT sessions. Both a strength and a plyometric programme also produced significantly greater gluteal activity in high-school females who took up a three-times-per-week, eight-week intervention; i.e., similar implementation to this study. Lephart et al. (2005) also found a decrease in hip- and knee-flexion moments, but no change in hip adduction or knee abduction.

However, significant improvements in gluteal activity following NMT are equivocal in the literature. Zebis et al. (2008) has found mixed effects on the gluteus medius both pre and post landing. After an NMT programme with elite adult female team sport players (football and handball), gluteus medius activity was observed to decrease significantly by 11% in the 10ms prior to IC, by 13% in the 10ms after landing and by 10% in the 50ms after landing (Zebis et al., 2008). This finding was observed during a sidecutting task. The authors suggest that these results may be explained by the different role that is played by the gluteus medius during a sidecut task compared with landing in the sagittal plane only.

Collectively, the gluteals have considerable influence on the kinematics of the body, since they control the pelvis and hip (adduction and internal rotation) and therefore affect proximal and distal segments and joints such as the trunk and the knee (Benke et al., 2009; Buckthorpe et al., 2019; Friel et al., 2006; Liu et al., 2012; Powers, 2010; Semciw et al., 2013). They also have significantly different effects on each gender (Hart et al., 2007; Zazulak et al., 2005). These muscles are powerful extensors that can affect movement in all three planes and, in conjunction with other muscles, can decrease the use of a dominant ligament during landing (Hewett et al., 2010).

Perhaps, in future studies, greater attention should be paid to gluteal activity, particularly to counter the change in this muscle’s use that is suggested by McGill (2007). McGill (2007) suggests that this muscle has been made redundant as altered lifestyles in the general population have led to the phenomenon of “gluteal amnesia”, and the work that would originally have been performed by this muscle has shifted to the lower back and hamstrings, which may lead to injury.

5.7.1 Kinematics

There were few significant kinematic changes in either the intervention or the control groups. There were no significant changes in trunk or ankle kinematics either within or between groups. This is consistent with the findings reported by Weir et al. (2019), who reported no significant changes in female hockey players following an NMT programme. There were, however, significant changes found in this study in the kinematics of the knee (abduction at MKF, maximum knee adduction and abduction and knee excursion).

Maximum adduction (which is often observed at IC) and maximum abduction at IC were found to be very small in this study (neutral for both groups in the sagittal plane hop and sidecut, and 3° (approx.) in the hop and twist); therefore, the landing mechanism was regarded as neutral. Hopper et al. (2017) reported that the frontal plane motion of ACL-injured athletes changed towards a neutral position during a course of NMT; the researchers reported IC knee abduction of -1.71° post-test from -5.66° pre-test during a single-leg landing task.

There were some significant differences in the maximum knee adduction during the sagittal plane hop. The data for the control group changed from showing slight abduction at pre-test to slight adduction at post-test, whereas the intervention group recorded the opposite change (CON = -0.8° to 1.3°; INT = 0.51° to -0.42°). Although these are statistically significant, these changes are small, contain a disproportionate amount of error due to the nature of markered motion capture systems, discussed in 2.13.6, therefore may cause a type 1 error and also may not alter the risk of injury. There were no notable changes during the hop and twist or the unanticipated sidecut for this variable.

There were some significant differences in the maximum knee abduction data for the sagittal plane hop. The figure for the control group decreased pre- to post-test by nearly 2° (however, no significant time*group effect), whereas that for the intervention group decreased by just 1°. The differences in the unanticipated sidecut were greater in the intervention group – a 2.4° decrease over the intervention period vs. no change in the control group. Decreases were recorded in the maximum knee abduction angles in the hop and twist and they were similar for each group. Overall, similar to maximum knee adduction, these changes are small and also may not change the risk profile of the players as ACL injured players had 9° of knee abduction (peak value), this is in contrast to a pooled mean peak of 1.4° (Hewett et al., 2005). Following the NMT intervention, the peak knee abduction values in this study were nearer the values reported by Meinerz et al. (2015).

Knee abduction has been established as a significant factor that contributes to ACL injuries, as this motion places the ACL under strain. The medial-anterior aspect of the lateral condyle of the femur, especially when combined with external rotation, appears to occur with peak ACL strain, which occurs between 40ms and 50ms after landing (Kiapour et al., 2014). Any movement in the frontal plane and transverse plane mechanics was encouraged to be limited through the corrective feedback particularly during the strength and plyometric sections.

In a prospective study, Hewett et al. (2005) found that knee abduction was a significant factor in the occurrence of knee-ligament injuries. They reported that the amount of knee valgus (hip adduction, hip internal rotation, knee abduction and knee external rotation) could be used to predict knee-ligament injuries ($r^2 = 0.88$) with 73% specificity and 78% sensitivity. Knee abduction peaked among an injured group of players (1.4° in the uninjured group vs. 9° in the injured group). With reference to these figures, the quantity of knee abduction that was observed in the control group in this study indicated that its members were at risk of ACL injuries (7.4 - 9°). The intervention group at pre-test could also be classed as at-risk (mean max knee abduction during the unanticipated sidecut was 10.9°), whereas after the NMT intervention period the risk level of this group's members was reduced, although the degree of abduction was considerably higher than the 1.4° that was reported for the uninjured group in the Hewett et al. (2005) study. The knee abduction results that were observed in this study (INT = 6.9 – 8.5°) were similar to those that were reported by Meinerz et al. (2015), which were 6.1° during an anticipated sidecut task and 5.7° in the unanticipated version. Therefore, the intervention group pare still at some risk of an ACL injury and could benefit further from the continuation of NMT.

The reduction in knee abduction that was recorded in this study in the unanticipated sidecut was greater in the intervention group than in the control group. The change between the pre-and post-test results was not as great as that reported by Hopper et al. (2017); during a vertical drop jump task, the Hopper study reported a 13.7° change in maximum knee abduction in the intervention group versus 7.2° at maximum knee flexion in the control group. The researchers reported a smaller change but a similar pattern during a single-leg landing task. However, the pre-test results reported by Hooper et al. were considerably higher than those found in this study. The reduced knee abduction reduces the knee abduction moments and therefore the strain on the ACL, and in turn, the incidence of ACL injury, and possibly medial collateral ligament injury.

Knee abduction during landing has been shown in a laboratory setting in this study, but in others, it has been recorded in field-based studies via video evidence (Koga et al., 2010; Olsen et al., 2004; Waldén et al., 2015). This knee-abduction mechanism, combined with limited knee flexion and a 'quadriceps-dominant' landing strategy, places the ACL under strain because of the angle of pull of the quadriceps tendon. This muscle activation strategy, which is especially prevalent in females, has been widely described as greater quadriceps activation, particularly of the rectus femoris (Zazulak et al., 2005) and the vastus lateralis (Zebis et al., 2008; 2015). Furthermore, there is evidence that there is a medial-lateral imbalance (Myer et al., 2005). This, coupled with a medial-lateral imbalance of the hamstrings, general anterior-posterior imbalance and especially with limited knee flexion (Hewett et al., 1999), leads to an increase in lateral and a decrease in medial joint compression. These changes reduce the active and passive resistance to knee valgus and ATT and cause medial femoral condylar lift-off (Ford et al., 2003), which results in increased strain on the ACL. Therefore, the focus of NMT programmes should be on activation of the medial muscles and, especially, the semitendinosus via Nordic Hamstring exercises and other hamstring exercises with both concentric and eccentric muscle contractions.

The knee excursion (difference between max knee adduction and max knee abduction) figures, which were recorded in all tasks, were much reduced in the intervention group at post-test compared with pre-test (a significant time*group interaction for unanticipated sidecut) . There was a larger decrease in the figures for the intervention group compared with those for the controls (CON = 0.3°, INT = 2°) in the sagittal plane hop. The main contributor to this result was a decrease in knee abduction in the intervention group. The pattern in the unanticipated sidecut was similar but more marked; the knee excursion in the control group increased (+1.2°) but decreased in the intervention group. The knee excursion data were similar for both groups in the hop and twist (the control group figure decreased by 1.5°, while the intervention group angle decreased by 1.7°).

The differences in knee excursion were due to small changes from slight abduction to slight adduction in the control group and vice versa in the intervention group. In addition, maximum knee abduction was decreased in the intervention group. The combination of these elements explains the statistical differences between the groups, with significantly less knee excursion in the intervention group. Knee excursion may have been limited through the focus on technique during the intervention. Furthermore, analogies, such as 'like a piston' encourage sagittal plane motion with the promotion of hip abduction and knee adduction during locomotion.

Some sagittal plane kinematics might have been expected to be observed and were observed in other NMT studies, but were not seen in this study nor in that by Weir et al. (2019). There was no group or time effect for the trunk, hip (bar flexion for both groups for SH and during USC in the intervention group), knee or ankle flexion. Greater flexion at IC was encouraged in both through the intervention content and the external-focused coaching points to prepare for weight acceptance. However, there may have been less reliance on the passive joint structures following the NMT as there was increase gastrocnemius activity. The recruitment of this muscle (and hamstring) can reduce internal flexion torques (Hewett et al., 2010).

Sagittal plane trunk and knee mechanics in this study were largely unchanged in this study from pre to post-test with a decrease in hip flexion. Increased sagittal plane flexion at IC has been reported in other studies (Lephart et al., 2005; Hopper et al., 2017; Nakagawa et al., 2013; Sasaki et al., 2019). This could be because the intervention was focused on plyometric and squat-based exercises and/or because of the design of the reference task. Increased knee flexion at IC suggests increased activation of posterior musculature prior to landing and therefore increased readiness for the subsequent landing forces. Proactive activation is important, as the latency period of the ACL-hamstring-reflex pathway is 120ms after stimulation (Krogsgaard et al., 2002). Furthermore, the increased flexion at maximum hip flexion and/or maximum knee flexion suggests increased force absorption and a muscle-dominant landing strategy (Hewett et al., 2010), which reduces reliance on passive structures and therefore possibly reduces injury incidence. However, it has been demonstrated that sagittal plane forces that act on the knee are not sufficient to injure an ACL during sidestepping (McLean et al., 2004). McLean et al. (2004) reported that anterior forces did not exceed 2000N, whereas valgus loads were sufficient to injure this ligament.

Increased sagittal plane trunk and hip flexion increases activation of the posterior chain musculature and reduces strain on the knee (Powers, 2010). Also, increased active trunk flexion increases hip and knee flexion (Blackburn & Padua, 2008). Greater trunk flexion is associated with ACL injury (Hewett et al. (2005) reported a difference of 10° between injured and uninjured groups). This could be because increased knee flexion leads to greater posterior pull of the hamstrings and reduced anterior pull of the quadriceps (along with muscle activation), which increases strain on the ACL (Sell et al., 2006). Greater flexion decreases the effect of vGRF on passive structures and joint compression, especially post-puberty (DiStefano et al., 2015). Changes in technique and use of plyometrics, which were included in the intervention in this study, have been shown to produce an extra 15° increase in knee flexion in basic training (Lephart et al., 2005). The aforementioned benefits were an intended outcomes from the intervention.

Landing in this study was often performed with a heels-first landing technique in all tasks. This was a focus of the intervention, particularly in the first section, with the feedback (an external focus) encouraging a softer landing strategy. A stiffer landing strategy has been shown to produce increased vGRF and increased RFD (Marinšek et al., 2010). The rate of force development in this study fell in range reported by others (from 2.5BWs/s (Yom et al., 2018) to 40BW/s (Quatman et al., 2006). Although the intervention group recorded a reduction in normalised GRF and the RFD after the intervention period, with a relatively simple change in technique these variables could be further reduced. The magnitude of normalised vGRF reported in other studies ranges from 1.9BW’s (Almonroeder et al., 2017) and 4.5BW’s reported by Yeow et al. (2011). A heels-first landing strategy is associated with reduced knee flexion, greater knee abduction and greater loading on knees and hips (Marinšek, 2010). This process is linked to the occurrence of ACL injuries (Yu & Garrett, 2007). In contrast, in toe-first landing, there is more tension in the Achilles tendon (Self and Paine, 2001) and greater activation of the ankle muscles (Nigg and Herzog, 1998) therefore, greater dissipation of landing forces. Furthermore, a softer landing strategy is associated with greater energy dissipation (eccentric work) by the hip extensors (Zhang et al., 2000).

5.7.2 Lateral trunk flexion

No significant differences in maximum lateral trunk flexion were measured during the three tasks. However, the intervention group showed a decrease in maximum lateral trunk flexion during the sagittal plane hop (3°) whereas the control group showed an increase during the unanticipated sidecut task with no change during the hop and twist. These results were observed despite the inclusion of exercises to develop core stability, balance and movement correction, improved technique (particularly during any change of direction) and to provide a stable foundation for movement (Hodges & Richardson, 1997) in the NMT intervention. This parameter is important, as trunk displacement has been found to be significantly greater in injured athletes than in uninjured, and lateral displacement has been reported to be the strongest contributory factor to knee ligament injury (Zazulak et al., 2007b). Other studies with a significant change (Hewett et al., 2005 and Paterno et al., 2004) in this parameter may have been due to the increase of core exercise rather than a multi-component intervention such as the one in this study. Maximum lateral flexion in this study, for both groups, was similar to the values reported by Zazulak et al. (2007) who reported maximum displacement of 9.5° (uninjured females), 13° (injured females) and 10° for all males. Therefore, the cohort in this study (both groups) are at risk of a knee, ligament or ACL ligament injury.

Injuries that are caused by low activation and/ or stability of trunk musculature can be rectified by the performance of targeted NMT that is focused on core stability, postural control and plyometrics (Hewett et al., 2017). Performance of NMT can alter proximal mechanics and reduce the injury risk profile, especially for high-risk groups. Also, exercises to improve trunk stability and activation of core musculature have been recommended by Pappas et al. (2016) to decrease the use during an unanticipated sidecut of trunk-dominant landing strategies (22% of females) and to improve knee alignment to assist those who are ligament dominant (14% of females).

5.8.1 Kinetics

There was a significant reduction in peak vGRFs (a significant time-group effect) in the intervention group for the hop and twist and unanticipated sidecut with no change in the control group. A 'softer' landing was encouraged during the plyometric and agility sections of the intervention with a greater range of motion and bracing during landing. Simultaneously, instructional feedback, such as 'land like a feather', was given. High GRFs are a significant factor in the development of knee injuries. Hewett et al. (2005) reported that GRF was found to be 20% greater in ACL-injured athletes than in ACL-uninjured. Furthermore, significant correlations were found between knee abduction moments, angle and peak vGRF and ACL injury ($r = 0.74$ and 0.67, $P < 0.05$) (Hewett et al., 2005).

The normalised vGRFs results in this study were 2.5BWs for the sagittal plane hop and hop and twist and 1.8 – 2.0BW in the unanticipated sidecut. The normalised vGRF was reduced in all 3 tasks in the intervention group (significantly in the hop and twist task). This may, in part, be attributed to the external focus coaching points mentioned earlier. This strategy can speed up the learning process and shorten the time to movement automaticity (Wulf et al., 2010) and develop more effective and efficient movement patterns (Wulf and Dufek, 2009). Evidence from neuroimaging studies shows the premotor cortex is active even when no movement occurs (Simon et al., 2002) therefore reducing the conscious attention to movement and can attend to other stimuli. Furthermore, learning with an external focus may enhance retention (Benjaminse et al., 2015). Benjaminse et al. (2015) also discuss how an internal focus, therefore conscious control, may limit automaticity, be more susceptible to anxiety and stress.

These results are also similar to those reported for anticipated and unanticipated drop jumps are 4BW and 2BW (approx.) respectively (Zhang et al., 2019) and to the normalised vGRF that has been reported during a single leg hop as 2.45BW for the dominant leg and 2.52BW for the non-dominant (van der Harst et al., 2007) and during an anticipated sidecut (2.44N/kg) and an unanticipated sidecut (2.37N/kg) (Yom et al., 2019). Kristianslund et al. (2014) found that those participants who sustained ACL injuries landed with a vGRF of 3.2BW, which was reached at approximately 40ms after landing, i.e., the typical time point at which ACL injuries are sustained.

Hewett et al. (1996) and Irmischer et al. (2004) introduced NMT sessions and subsequently measured reduced vGRFs. However, vGRFs were not always significantly reduced following an injury prevention programme (Vescovi & VanHeest, 2010; Vescovi et al., 2008), although reductions were observed. In addition to NMT, the participants in one study were given augmented feedback. This addition to the programme had a significant effect on the vGRF; the feedback was found to reduce vGRF by 23.6% ($p = 0.001$) (Cronin et al., 2008). A reduction in vGRF has been associated with sagittal plane mechanics (Khuu et al., 2015). For example, greater hip (+8.4°) and knee flexion (+6.5°) during landing has been reported after NMT along with significant reductions in vGRFs (Hopper et al., 2017). In addition, greater ankle dorsiflexion with a toes-first landing strategy produced reduced vGRFs and RFDs compared with a heels-first strategy (Yeow et al., 2011).

In this study, the RFD in all tasks was increased in the control group and decreased in the intervention group (a significant between group difference for the sagittal plane hop and a time-group interaction in all tasks). In the sagittal plane hop, an increase of 0.3BW/s was measured in the control group, while a decrease of 1.7BW/s was observed in the intervention group. The pattern was similar in the hop and twist, with an increase in the control group's RFD (0.4BW/s) and a decrease in the intervention group's RFD (0.7BW/s). The same pattern in the unanticipated sidecut produced a greater difference; a 6.1BW/s decrease in the intervention group and a slight increase (1.2BW/s) in the control group (figure 5.12)

These RFD differences may be due to landing technique. The significantly reduced RFD in the intervention group could be due to the greater ability of this group to dissipate energy. The knee extensors and ankle plantarflexors are key contributors to this process and the increased activation of these muscles in this study could lead to greater energy absorption. The knee extensor muscles were observed to be more activated following the intervention period and, therefore, these muscles, rather than passive structures such as ligaments, could be dissipating the kinetic energy resulting in the RFD as well as peak vGRF will be reduced during landing, therefore, reducing the injury risk. The use of this landing strategy would suggest that the intervention group adopted more of a 'muscle-dominant' landing strategy than the control group. This may have been due to the corrective external-focus feedback that was provided in the intervention, as well as the inclusion in the intervention of some exercises such as the bounding, plyometrics and agility exercises.

The dissipation of forces can occur via several structures. Ideally, this would be via musculotendinous structures of the lower extremity during uni- and bi-pedal landing. Also, this would be via the large muscles, as these have a greater capacity to dissipate forces because they have larger cross-sectional areas, longer muscle fibres and shorter tendons than small muscles. This requires the transfer of energy from distal to proximal structures; therefore, the peak work at distal musculoskeletal structures will occur before that at the proximal structures (Zhang et al., 2000). Zhang et al. (2000) reported that more work was done by knee and hip joints and associated muscles during softened landings. The contribution of the ankle to energy dissipation during single-leg landing (sagittal plane) is 45.7%, the contribution of the knee is 11.4% and that of the hip is 42.9% (Decker et al., 2003). Therefore, greater work is performed by the hip and ankle extensors than by other muscles. In the frontal plane, during single-leg landing, the contributions are 36.6% from the hip, 60.7% from the knee and 2.7% from the ankle (Decker et al., 2003). Therefore, knee abductors provide most of the energy dissipation as vGRF is increased. During double-leg landing, the contributions are 66.7% for the hip, 29% for the knee and 4.3% for the ankle. The knee in this task dissipates less energy than it does in single-leg landing, but more than it does in sagittal plane motion (Yeow et al., 2011). Also, single-leg landing is generally stiffer than double leg, therefore there is greater knee contribution in the single-leg landing than in double leg and a higher risk of ACL injury (Lephart et al., 2002). Furthermore, there is greater motion in the frontal plane during single-leg activities than in double leg, which again increases the risk of ACL injury.

5.9.1 Performance

Performance has been an outcome of NMT interventions (2.7) and may be of interest to both coaches and players. The measure of performance in this study, calculated as the height achieved during the hop and twist task, was found to be similar both within and between groups (15-17cm in all cases a non-significant change). The performance improvements could have been observed with the inclusion of strength and plyometric exercises in the intervention. All the studies above involved measured performance with separate tests, whereas the performance test in this study was integrated into a task (the hop and twist). Therefore, the focus of participants may have been on the landing after this task rather than on the performance of the hop. Performance improvements have been reported previously, although jumping performance did not improve following a plyometrics programme with female college basketball players (Vescovi et al., 2008). The jump heights that were reported in this study were slightly higher than those found by van der Harst et al. (2007), who reported jump heights of 12-13cm, but lower than those reported by Chappell and Limpisvasti (2008). More pertinently, these authors reported a significant increase in performance following NMT. A significant increase in performance was also reported by Hewett et al. (1996), Myer et al. (2005), Ford et al. (2005), Zebis et al. (2008) and Noyes et al. (2013).

Significant performance improvements have also been reported in NMT programmes with female hockey players in upper and lower body strength, 40m sprint speed and aerobic capacity (Weir et al., 2019). However, the intervention period was much greater (up to two seasons) than in this study (eight weeks) and included a nine-week intensive period of four sessions per week. Furthermore, as the study involved elite athletes, some strength and conditioning programmes may have played a role in addition to skills training and performance in competitions; however, this was not reported.

5.10.1 Compliance

The compliance rate for intervention group this study was 66.9% and 68 for the controls. This level of compliance could be attributed to the design and implementation of the programme. The NMT programme was multi-component and delivered with supervision, encouragement and feedback from the primary researcher. This level of compliance may explain some of the small changes over time. This programme with greater compliance (some participants had 90%+ compliance with some much less) may have elicited greater changes. As there were few injuries recorded during the intervention period, non-compliance may be accounted for by external factors such as work or other pre-standing obligations. The researcher as the instructor may have increased the compliance (and possibly effort) compared to a 3rd party delivering the intervention. Although the affect is hard to measure and evaluate. This could be a part of a wider compliance study in the future.

Sugimoto et al. (2012) found that mean compliance with exercise programmes across the literature was 45.3% with a large range, from 10% to 100%. These authors classified >66.6% as high, 33.3-66.6% as moderate and <33.3% as low. They found that compliance had a marked effect on the prevention of injury; those who complied moderately with the requirements of the intervention were 3.1 times more likely to injure an ACL than those who were highly compliant. Furthermore, another study found that a high compliance rate to an NMT programme resulted in an 88% reduction in the ACL injury rate, whereas those in a low-compliance group showed very similar ACL injury rates to those of a control group (Hägglund et al., 2013).

The compliance rates for NMT programmes vary and the reasons often not evaluated. A future study to investigate how compliance, motivation and effort during interventions such as this could investigated in future. In longer interventions, a progressive approach could be taken to maintain interest. Some of the high-quality studies report low compliance, 10.7%, (Steffen et al., 2008) and 31.3% (Söderman et al., 2000), moderate compliance, 45.2% (Hewett et al., 1999), and 44.1% and 50% (Myklebust et al. (2003) and some high, 69.7% and 70.4% (Kiani et al., 2010) and 100% (Heidt et al. (2000). However, not all studies have reported compliance rates (Grindstaff et al., 2006).

Compliance may be linked to the structure and implementation of the programme. A lack of consistency was identified by Steffen et al. (2008) as a factor in low compliance rates, as was a lack of supervision coupled with an intervention that comprised a single component (Söderman et al., 2000). Those participants who undertook interventions that maintained participant’s motivation had higher compliance rates. Motivation came in the form of encouragement from the coaches to attend (Heidt et al., 2000), newsletters (Kiani et al., 2010), an intervention that involved multiple components (i.e. exercise variation) and supervision (Sugimoto et al, 2012). These factors were considered in the design and implementation of the intervention that was used in this study.

The compliance rate for Soligard et al. (2008), who implemented the popular FIFA 11+ programme, was 77%, the compliance rate that was reported by Weir et al. (2019) was 88.2% and a median compliance rate of 84.3% was found by Barboza et al. (2018). These studies have greater compliance than in this which may contribute to the greater changes that were observed. The high compliance rate was reported by Weir et al. (2019) could be explained by the multi-component programme and supervised elite athletes used (with a coach-athlete ratio of 1:13). Weir et al. (2019) not only measured attendance and compliance but also engagement, motivation and perseverance. All were high (81%, 88%, 89%, 90% and 92% respectively). This level of compliance and supervision may have contributed to some of the changes observed, particularly performance. The coach-athlete ratio was lower in this study (1:20).

5.11.1 Components of the intervention

The intervention was designed to include all the elements that theoretically could elicit a prophylactic response, i.e. strength exercises (especially Nordic hamstring exercises), and drills for balance/proprioception, agility, plyometric training (jumping) and sport-specific movements. This design followed the guidelines that have been developed through meta-analyses by Emery et al. (2015) and Sugimoto et al. (2012; 2015; 2016) with an intervention period that has been demonstrated to be optimal, i.e. approximately 15-20 mins per session at a rate of three sessions per week and a total intervention period of less than six months (Steib et al., 2017; Sugimoto et al., 2014). The inclusion of these elements ensured some variation and therefore maintained motivation. Some interventions that have been used by other studies have included further features to maintain motivation. These interventions such as the FIFA 11+ (Soligard et al., 2008) and the warming-up hockey programme (Barboza et al., 2019) were developed to include different levels of difficulty. The FIFA 11+ comprises three levels to provide progression and natural variation. Warming-up hockey is a long programme that classifies exercise schedules according to gender and age. This progressive structure was not incorporated into the NMT programme that was used in the current study. Such a change in structure could be considered for future research. A progressive structure to increase the intensity and could be applied particularly to elements that produced minimal changes in this study, for example, hamstring and gluteus maximus activation and knee flexion.

5.11.2 Other implementation recommendations

Other important elements of NMT programmes include augmented feedback on biomechanical technique which was found to be an important part of training programmes. Myer et al. (2013) found that the addition of augmented feedback to reduce frontal plane knee angle during a tuck jump led to a 37.9% reduction in the angle compared with a 26.7% decrease in the control group that did not receive the feedback. Furthermore, feedback with an external focus can increase the skill acquisition efficiency Benjaminse et al. (2015) discuss that the use of explicit, internal instructions regarding, for example, landing mechanics may interfere with motor learning and therefore performance. Therefore, explicit learning may inhibit automaticity. Benjaminse et al. (2010) also discuss the precise processes associated with this are still unclear. However, Benjaminse et al. (2015) indicated an external focus reduces the time of initial learning and increasing the activity of the premotor cortex which is involved in the preparation and execution as well as the memorization of movements for enhanced retention.

Similarly, the use of video and/or expert feedback can have a prophylactic benefit; Onate et al. (2005) reported that the addition of these facets led to increased knee flexion angles and reduced vGRF. This prophylactic benefit was also found during a landing task that was performed by volleyball players, who achieved a 23.6% reduction in vGRF when this benefit was incorporated (Cronin et al., 2008). Also, an external focus with a visual feedback component that is provided in a positive manner can improve the performance of jumping and landing (Benjaminse et al., 2015). These considerations were also adopted in this programme by giving external coaching points for each exercise.

5.12.1 Practical implications of this study

The evidence from this study suggests that there are benefits to performing neuromuscular training before both training and competition rather than continuing with the current practice. In this study, muscle activation was altered for only some muscles and at some time points, reduce knee abduction, reduce vGRF and the RFD compared with the control group who performed their usual warm up. A NMT programme can also replace current practice as NMT can be completed in the same duration (> 20 mins) and can be completed without any specialised equipment as only equipment that is usually needed for hockey sessions were needed (cones, whistle, stopwatch, hockey sticks and balls). To implement this NMT programme completely, some education or support materials may be required so the feedback and technique elements and concepts can be understood and applied correctly. Materials such as posters and video support have been provided to assist the delivery in other NMT programmes (Barboza et al., 2019; Olsen et al., 2005; Soligard et al., 2008)

5.13.1 Strengths, limitations and future directions

This study deployed a controlled-trial design rather than a randomised, controlled trial design. Randomising or Latin-square design could be used, to reduce systematic errors, in future studies. This choice limited the veracity of this study; however, this study involved the comparison of any changes that were observed with those that were produced in a control group. Furthermore, the profiles of the groups showed large similarities in many elements apart from the number of years during which the participants had played hockey. Every effort was made to keep the conditions the same (scripts, data collection processes and the time of year at which the studies were undertaken – i.e. within the hockey season). However, a randomised, controlled trial is always a more desirable research design.

During the testing procedure, the data from five trials that were undertaken by each participant in each task were collected rather than three. Data collection from a greater number of trials would have improved the veracity of the data and greater efficacy in the mean. Data from the first five successful trials were collected and analysed rather than the first five trials that were performed. The latter approach may have highlighted greater differences between the groups, especially in muscle activation and variability.

The sample size in each group was sufficient for a study of this nature, i.e., there was a greater sample size than that required according to the power analysis (according to Zebis et al. (2015), 17 participants to detect a between-group difference of 15% normalised EMG with an SD of 15% is required). In addition, the sample was larger than those used in similar studies (Donnelly et al., 2015; Weir et al., 2019). However, a greater number of participants in this study would increase the efficacy and potentially avoid a type 2 error. A power-analysis for kinematic variables indicates that a much larger sample size may be required, especially to account for soft tissue artefacts. The sample size in this study was 18 hockey players in the control group and 20 in the intervention group, which is within the mean range (15-42 participants) that is required to undertake research in biomechanics (Knudson, 2011). A larger sample size may have reduced the likelihood of finding differences by chance. Further, multiple variables measured and analysed in this study may have led to significant differences being found by chance.

Another methodological limitation was the use of reflective markers to measure kinematics. Although the use of reflective markers is a common approach, soft tissue artefacts could lead to as much as 12.6mm of variation in the movement of the lateral knee marker, with greater movement in the thigh compared with shank markers (Akbarshahi et al., 2010). Also, the calculation of hip-joint motion appears to underestimate movements, with the thigh contributing more than the pelvis (D'Isidoro et al., 2020). Therefore, soft tissue artefacts could mask changes in kinematics or exaggerate small changes or small movements. There was an attempt in this study to reduce the effects of soft tissue artefact (STA), by placing tracking markers on rigid plates. Ding et al. (2020) also recognise this issue, especially for the thigh rather than the shank, evaluated the use of a thigh clamp and found this device reduced rotation and transverse plane also inter-operator reliability. Maybe, future studies will benefit from a markerless system (Strutzenberger et al., 2020) to avoid some of the procedural errors and issues of a markered system such as joint centre identification, soft tissue artefact and, sometimes, discounting successful trials as an error occurred, such as the detachment of markers.

There were some changes in the EMG, kinematics and kinetics by both groups however, the performance was unchanged. The former may have elicited a change in performance however, the performance measure was incorporated into a more complex manoeuvre therefore, any changes may have been masked. A separate and distinct performance task could be used in any future studies.

The compliance to the intervention was high; however, there was a very wide variation in compliance among the participants (from around 30% to 90%+). The greater the compliance, the greater the effect (as discussed above). An investigation into alteration in the variables compared with the level of compliance could be conducted in future. A more desirable compliance rate would be 66%+ for all participants, which might have produced clearer differences between the groups. The intensity of the effort and level of motivation that each person put into the exercises were important factors that the researcher found difficult to control. In this study, the author delivered the intervention, which helped to ensure that all the exercises were completed as required. This decision led to accurate monitoring of attendance, which could be a source of error in other studies. This delivery mechanism could also improve the quality of the execution of the exercises. The quality of the execution could be a limitation of other studies that required coaches or athletic trainers rather than the researcher to deliver the intervention. The compliance and the effects of the intervention on outcome measures have been reported; however, the quality of execution and its effects on the outcome measures could be a subject for further research. Studies that involve a more elite group of hockey players and a greater level of compliance, effort and motivation may make this achievable.

The performance measure in this study was the hop during hop and twist which showed no difference between or within groups. This may be due to the task being part of a task (i.e. the hop during the hop and twist) rather than being a separate, stand-alone activity. This may have affected the results. A separate performance task could be considered in future studies.

5.14 Conclusions

This study presents some evidence that exposure to a NMT programme may have a preventative effect on the occurrence of some hockey injuries. This NMT programme altered some muscle activity, decreased knee abduction and excursion and led to a reduction in peak vGRF and RFD. However, there was no change in performance.

With the evidence that was provided by this study, the null hypothesis can be partially rejected; there was a measurable difference between the intervention and control groups following a NMT programme among recreational adult female hockey players. The difference suggests that the programme may have had a prophylactic effect. Future studies could investigate the effect of NMT on performance and on other hockey-playing populations, such as male players. Also, higher intensities, mechanisms to ensure higher adherence and higher training volumes can potentially introduce greater changes after a NMT programme.

Chapter Six General discussion and conclusion

6.1. Introduction

This chapter will discuss the main aim, findings and the implications of each of the studies that were carried out as part of the work for this thesis. Also, the limitations of the studies and suggested future research will be discussed. This chapter will finish with general conclusions.

The broad aims of the studies, which were largely met, were to investigate:-

1. The nature, severity and mechanisms of occurrence of non-contact injuries in Scottish hockey and the characteristics of those who sustain them (Chapter 3);

2. Current practice and coaches' perceptions of the warm-up in hockey in Scotland (Chapter 4); and

3. The biomechanical effects of an NMT programme on female hockey players (Chapter 5).

6.2 Summary of results for each study

6.2.1 Study 1 – Hockey injury questionnaire

This study aimed to investigate the occurrence of non-contact injuries in hockey. Following responses to an injury questionnaire (n = 317), the results of this study showed that the rate of injury was 4.09 injuries per1000 hours of hockey play (both match and training) overall and that 31.4% resulted in no time loss from the game, 17.4% led to the next session being missed and 19.8% resulted in the loss of two to four weeks of play. These injuries were largely to the lower extremity (87%), specifically knees (21.4%), hamstrings (21%) and ankles (9.9%), with similar injury rates among both genders and for all positions, ages and levels. The majority of the injuries occurred during sidecutting (19.6%), acceleration (13.8%) and landing (12.9%), which resulted in muscle damage, strains, sprains and pulls (48.3%), ligament damage (19.2%) and abrasions (4.9%). These injuries occurred often in training (31%) or during the second or third quarters of a match (13.9% and 18.9% respectively) during the first half of the year, particularly between September and November, which is during the season. Hockey players appear to undertake little neuromuscular or injury prevention training, and coaches offer little advice or direction regarding either injury prevention or the best exercises to perform in a warm-up to promote injury reduction or to improve performance. The evidence in this study shows that rate, anatomical site, mechanism and nature of noncontact injuries suggests that the main mechanism of injury (i.e. the warm up) warrants further investigation.

6.2.2 Study 2 – Current practice of hockey warm-ups

This study aimed to investigate the current warm-up practice among recreational hockey players in Scotland through observation of warm-ups at all levels and in all areas of the country (n = 17). The results of the warm-up observations suggest that the warm-ups last up to 23.3 minutes with some pulse-raising (up to 14.5mins) and skill-rehearsal (up to 12mins) exercises; or the warm-up can be broken down into two minutes of pulse-raising, five minutes of activate and mobilise, eight minutes of potentiation and four minutes of recovery. This pattern was similar across genders, ability levels and by coach qualification. About 41% of the warm-ups involved static stretches, whereas NMT was rare (it was seen only in two of the 17 observations). Furthermore, 33% of all warm-ups contained no hockey-specific exercises; 28% included ‘drill’-type exercises and 22%

involved static skills rehearsals. In the post warm up questionnaire, most coaches showed that they had considerable hockey experience, coached regularly and devised their own warm-ups from previous experience and observation of others. Interestingly, the warm-up itself was often conducted by a player, yet most coaches would prefer to alter this approach to include position-specific exercises, injury prevention/proprioception exercises, and small-sided games over a longer duration than was used. Therefore, with the current practice being sub-optimal, an investigation into the effects of an alternative warm up, including injury prevention exercises, is warranted.

6.2.3 Study 3 – Effect of NMT on female recreational hockey players

This study aimed to investigate the effects of a neuromuscular warm-up on recreational female hockey players. This study, which compared an intervention group (n = 20) against a control group (n = 18), showed few significant differences between the NMT group and the controls, who performed their usual warm-ups. Both groups improved muscle activity both prior to and post landing, but there were greater increases, some significant, for some exercises that were performed by the intervention group. There were some significant kinematic differences; the intervention group showed significantly less knee abduction and knee excursion after eight weeks of NMT. Changes in the kinetics were also apparent; the intervention group’s peak vGRF was reduced following the programme whereas that of the control group was increased, while the intervention group recorded a significant reduction in the RFD after the study period whereas the control group showed a slight increase. Therefore, a decreased risk of injury.

6.3 General discussion

6.3.1 NMT and injury rates

Compared with a control group, the performance of sports-specific NMT helps to reduce some risk factors that may cause injury, for example, knee abduction, peak vGRF and RFD. These changes may be related to increased muscle activity, particularly the gluteals. These changes may modify kinematics and dissipate landing forces that protect passive soft tissue and reduce injury rates. Other NMT interventions in hockey have shown this to be the case; for instance, Barboza et al. (2019) found that, among recreational youth hockey players, the risk of injuries was reduced (shown in terms of 8.42 fewer days lost per 1000 playing hours) by performance over a 40-week season of a 12-minute warm-up that included preparation, movement and field-hockey skills. Further, Weir et al. (2019) found a significant decrease in the number of ACL injuries to elite female hockey players (zero vs. 0.04/1000 playing hours for a control group) and the high-risk athletes in the group reduced their knee valgus moments by 30% as performance increased.

Similar outcomes have been found in other injury prevention studies that have investigated injuries sustained by females in team sports. For example, an 11% decrease in overall injury rates and a 6% decrease in ACL injury rates were reported after completion of the NetballSmart programme (Kearney, 2019) (see 2.8). Similarly, up until the publication, this programme has been implemented for 1.5 years. a cluster-randomised controlled trial among female youth football players, there was a reduction in injury levels with significant reductions in the risk of sustaining an injury (overall, RR = 0.68), overuse injuries (RR = 0.47) and severe injuries (RR = 0.55) (Soligard et al., 2008).

NMT programmes that were aimed at reducing rates of occurrence of specific injuries or injury mechanisms were also shown to be effective. The evidence that was presented in chapter 3, which was performed as part of the work for this thesis, showed that knee, ACL, ankle injuries and injuries sustained during sidestepping (injury location and mechanism respectively) were more prevalent in hockey than in other sports. Firstly, regarding knees, other researchers have found that numbers of knee and ACL injuries can be significantly reduced through the performance of NMT (Hewett et al., 1999) with an odds ratio of 0.51 (95%CI, 0.37-0.69) across all studies (Petushek et al., 2019). NMT programmes to reduce rates of ACL injury have been shown to have a positive effect on knee abduction, knee flexion (Hopper et al., 2017), peak vGRF (Hewett et al., 1999; Vescovi et al., 2008) and RFD (Irmischer et al., 2004). All these changes bar those to knee flexion were observed in this study.

Secondly, ankle injuries, specifically to the ligaments, were the third most common injury in this study. They also frequently occur in other team sports (McGuine et al., 2000), often during landing. Ankle injuries often occur because of a combination of inefficiencies of the sensorimotor system and kinematics. This issue can be addressed by the performance of the balance and proprioception exercises that were included in this study and which activate the muscles that control the ankle joint (Borreani et al., 2014). Furthermore, ankle kinematics (increased flexion range of movement and limited eversion) can be altered to reduce the load on the ankle (Volkerding & Ketcham, 2013) and strain on the passive structures such as the ligaments. This study did not observe any increase in the range of motion of ankle flexion; however, a 'soft' landing strategy was encouraged, which led to a significant reduction in RFD. The decrease in RFD may be attributed to the greater gastrocnemius activation following neuromuscular training. This increase may also increase ankle stability. The decrease in RFD was consistent with the results of a knee injury prevention programme that was tested in a group of adolescent female soccer players (Irmischer et al., 2004). A 'soft' landing strategy is associated with reduced energy dissipation at the ankle (Decker et al., 2003). Therefore, the implementation of NMT could reduce ankle injury rates.

The factors listed above were also observed during a sidecutting manoeuvre (Bencke et al., 2013). This manoeuvre is frequently associated with injury in hockey (Chapter 3) and other invasive sports. NMT can improve the mechanism of this movement by reducing knee abduction moments during a sidecut and side hop (Celebrini et al., 2012). The latter study also reported greater maximum knee flexion during landing. This change in movement pattern may occur as a result of increased semitendinosus activity both before and after landing (Zebis et al., 2008; 2016), although not observed in this study.

This evidence suggests that the performance of NMT can have a positive effect on reducing the occurrence of the most prevalent injuries to the lower extremities, whether the improvement is measured by injury rates or by biomechanical analysis of known risk factors. Maximum knee abduction and knee excursion were significantly reduced in this study

6.3.2 NMT and performance

No significant change or difference in performance was measured in this study. This may, in part, be due to the integration of the performance assessment into the hop and twist task rather than its study as a separate activity. Also, although the intervention elicited some changes in muscle activation that were greater than those of the control group, the changes may not have been enough to improve the performance. The intervention period may need to be extended to produce performance benefits and include some progressions. The success of some NMT programmes that have been implemented in sports teams has been assessed through measures of injury rates during play rather than in a laboratory setting, for example, in football (Soligard et al., 2008) and hockey (Barboza et al., 2019). However, programmes that are focused on injury prevention can also improve performance (Hewett et al., 1999; Hopper et al., 2017; Neto et al., 2017; Pasanen et al., 2009). The most pertinent example is the study by Weir et al. (2019), which reported significant improvements in strength, sprint performance and aerobic endurance following intensive training, as well as a significant reduction in lower extremity injury rates.

6.3.3 NMT and current practice

There is limited published literature on the current practice of warm-ups. Current warm-up practice in golf suggests that it is not adequate to achieve performance or injury-prevention goals (Fradkin et al., 2001). However, in semi-elite hockey, warm up practice appears to be at the other end of the spectrum; in a study by Avest (2010), the average length of a hockey warm-up was reported to be just over 35 minutes, with some coaches wanting longer sessions, although there was a wide variation between coaches. In contrast to Avest, the study in this thesis (Chapter 4) showed that warm-ups were shorter than recommended in the literature. Also, NMT training was observed on two occasions, whereas static stretching was observed on 44% of all warm ups. This may be because coaches designed their warm ups from their own experience when static stretching was supported by coach education. There may be an opportunity for updated knowledge in this area as static stretching, as an injury prevention mechanism, appears to have limited support. Small and Naughton (2008) conclude, with a study into the efficacy of static stretching (with only RCT's and CCTs included), that there is moderate to strong evidence that static stretching does not reduce overall injury rates. The effect of static stretching on performance appears to be equivocal, apart from activities involving a large range of motion, with some authors suggesting that it has no or even a negative effect on performance, especially the ability to produce maximal force (Hadala and Barrios, 2009; McHugh and Cosgrave, 2010; Young, 2007). The negative effects can be mitigated by low-intensity and practice activities and it is recommended that static stretching could be replaced (Young and Behm, 2002).

Therefore, with support for the exclusion of static stretching for both injury prevention and performance enhancement, the current practice could be improved. Dynamic stretching, which is supported (Young and Behm, 2002), was frequently observed in this study, as part of the active and mobile section, has been recommended (Cone, 2007; Jeffreys, 2007; Young and Behm, 2002). However, the current practice could be improved with NMT as there has been considerable support for both injury prevention (Emery et al., 2015; Leppanen et al., 2014) for hamstring (Mendiguchia et al., 2015), knee (Monajati et al., 2016; Sugimoto et al., 2015) and ankle injuries (Caldemeyer et al., 2020). The evidence from chapter 5 of this thesis and the evidence from Barboza et al. (2019) and Weir et al. (2019) suggests that wider use of NMT would both reduce injury risk and enhance performance.

The attitude towards warm-ups is also an area for improvement. The aforementioned Fradkin study into warm-ups in golf suggested that there was an educational opportunity as, if players were instructed in how to warm up, they were three times more likely to do so than those who were not informed. It was also reported that instruction would lead golfers to warm up more frequently (Fradkin et al., 2001). A similar lack of awareness among other sports players may be the reason why, as this thesis has shown, there is limited application of NMT in sports warm-ups. However, it has been shown that, if netball coaches are taught about the potential benefits of incorporation of exercises that guard against injury, their attitude is altered towards the warm-up (White et al., 2014). There is contradictory evidence regarding attitudes towards warm-ups in football; although both players and staff are motivated to complete a warm-up, injury prevention is not a benefit that a warm-up is seen to provide (Towlson et al., 2013). This suggests that the attitude of coaches (and players) to hockey warm-ups could be changed with education.

The primary focus of this intervention was injury prevention, with a secondary focus on performance. This focus was in contrast to that of the coaches who were questioned in chapter 4 of this thesis. The focus of these coaches was pulse raising, mental preparation and stretching. Injury prevention was not an outcome of a warm-up, according to the coaches questioned in Study 2. Intriguingly, most coaches would have liked to have had different warm-ups from those that were performed, despite the majority of the coaches having devised the warm-ups themselves. This may have been due to conflicts between coaches and players, as player adherence to coaches' instructions is a challenge (Fradkin et al., 2001; McCall et al., 2016). Coaches in this study expressed their desire to include more exercises that involved greater intensity and focus. Position-specific and injury-prevention exercises, and skills rehearsals, were also desired by coaches, and the adoption of NMT would fulfil these requirements. The coaches also wanted to extend the warm-up to include injury prevention, position-specific and small-sided game exercises; these were sought to improve performance and the tactical or psychological components of competition. However, the coaches' perceptions, from the evidence in the post warm up questionnaire, are that they considered injury prevention to be a less important benefit of a warm-up than other outcomes as injury prevention was not mentioned as a desired outcome. Although, injury prevention exercises were mentioned as an element to include in future warm ups.

6.3.4 Practical implications

There are several practical implications of this research. The evidence provided in this thesis highlights noncontact injuries, current warm up practices and that a NMT-style warm up could be incorporated into normal practice and may have an influence on noncontact injury rates. If a NMT-style warm up adopted as normal practice then a progressive programme would be required to physically challenge hockey players and also to maintain or improve compliance. Regular and consistent performance of NMT could reduce non-contact injury risk and fully achieve the aims that coaches have for a warm-up. Furthermore, the evidence could inform the advice and education that is provided for coaches by national governing bodies. An NMT-based warm-up could also be adopted by hockey authorities such as the European Hockey Federation and the Federation Internationale de Hockey. Such adoption of this approach to warm-ups by hockey institutions would increase awareness and therefore the numbers of coaches who implement NMT in their warm-ups and the number of players who perform it. Adoption of this practice would also lead to improved fulfilment of the responsibilities of the coach and governing bodies, as described by Fuller et al. (2007).

6.4 General limitations, conclusion and future directions

6.4.1 General limitations

Whilst the results of the studies, with some justified methods, in this thesis, showed some interesting results, there are some limitations. In study 1, there may be some value in structuring the questions differently with more open questions. This approach could also be adopted for the post-warm up questionnaire for coaches. There may also be some value in comparing (using the same variables in study 1) contact and non-contact injuries. In addition, there may also be value in developing the different perspective of players and coaches with regard warm ups. This angle was not explored in depth in this study. The final alteration to the method in this thesis could be in study 3 with the exploration of compliance, effort and commitment to neuromuscular training.

6.4.2 General conclusions

The injury epidemiology study that was conducted as part of the work for this thesis provided evidence of the occurrence and characteristics of injuries in hockey, and it was the first study that had focused explicitly on non-contact injuries. It was found that current warm-up practice could be improved through the education of coaches and players to adapt to a more evidence-based approach and implement NMT in their practices. This evidence could be disseminated through coach education provided by Scottish Hockey. This is reinforced by the fact that current warm-ups rarely include NMT but more often include static stretching. Finally, it has been shown that NMT may have a positive impact on some modifiable biomechanical factors, which could result in the reduction of non-contact injuries. In total, the evidence provided in this thesis could inform current warm-up practice and, hence, could lead to reductions in some risk factors and improvement of movement during hockey play.

6.4.3 Future directions

Each of the studies that were performed for this thesis could progress further. The injury epidemiology study in Chapter 3 employed a retrospective hockey injury survey. Epidemiological evidence collected prospectively on non-contact injuries in hockey from further afield, such as the United Kingdom or across Europe are needed to clarify the picture of non-contact injuries in hockey. Alternatively, an investigation solely into non-contact injuries at the elite level would also further our knowledge in this field.

A more ambitious investigation could be undertaken to monitor injury rates after the implementation of the NMT programme that was introduced in this project to a wider hockey-playing population (e.g. age, gender, playing standard) in Scotland over a longer time period (a full hockey season). Therefore, a study of the effects of NMT implementation from an injury-prevention perspective would provide a complete picture of the effects of this mode of training on hockey players. Such an investigation could also lead to modifications of the programme for specific groups such as goalkeepers (i.e. FIFA 11+ kids and referees). For instance, modifications could be introduced in response to prominent mechanisms of injury such as changing direction in a crouched position or to improve strength and balance on one leg while twisting both, which is a movement typical of hockey play.

A progression from the observation study would be to explore further (qualitatively) the attitudes among players towards current warm-up practices. These attitudes affect adherence to and completion of the warm-up. An investigation such as this could also highlight the barriers to change and the incorporation of NMT into training and warm-ups. These challenges have been investigated in other sports. McCall et al. (2016), in elite-level football, reported that, although injury-prevention strategies were frequently implemented, poor levels of adherence, quality of execution, and coach and player compliance negatively affected the effectiveness of these programmes. A subsequent investigation into different approaches that could enhance adherence to warm-ups to increase compliance, motivation and completion rates could include education, feedback or involvement of technology. Furthermore, a study into the expectations of a warm up from a coaches and players perspective compared to the literature.

The results of the NMT programme intervention study show that there was less improvement in activation of the hamstring muscle compared with the improvements that were reported in previous research (Petersen et al., 2011; Wilderman et al., 2009; Zebis et al., 2016). Therefore, a further investigation into the development of this important muscle for hockey players would be useful. The lack of change in the intervention group could be attributed to the level of compliance, an investigation into compliance with a warm up such as this may be interesting. This may show the issues of changing from current practice to a NMT-based warm up on a long term basis.

An ambitious development would also be the prospective assessment of the effects of an NMT programme on injury prevalence among both male and female hockey players. Specifically, this would involve the employment of a cluster randomised controlled trial among higher risk hockey players, particularly in adult-led groups. This approach would increase the ecological validity of the study. Also, a longitudinal study into the injury rates of those performing a NMT warm-up compared to a control group.

6.5 Thesis publication plan

The studies that were performed as part of this thesis are under consideration for publication. The studies in Chapters 3 and 4 have been presented as a poster at the International Sports Science and Sports Medicine Conference (2016). The thesis chapters are currently drafted in journal paper formats with the aim to send these for publication in a sports science or sports medicine journals in the near future. Some of the target journals are shown below.

1. The incidence of non-contact injury in field hockey in Scotland (Study 1); *American Journal of Sports Medicine* (impact factor, 5.81)

2. Current warm-up practice and coach perceptions in field hockey (Study 2); *Journal of Science and Medicine in Sport* (impact factor, 3.61).

3. Effects of a novel neuromuscular training programme on recreational female hockey players during a sagittal plane hop, hop and twist and unanticipated sidecut (Study 3); *Scandinavian Journal of Sports Medicine* (impact factor, 3.26)

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Appendices

Appendix 2.0 Hockey epidemiology

Author / Date	Population	Injury rate / 1000hrs (unless stated)	Position	%	Mechanism	%	Body part injured	%
Fuller et al. 1990 (Via Barboza et al.2018)	Females	-	Goalkeeper Defender Midfielder Attacker	4 16 37 37	-	-	Knee Hand wrist finger Thigh Head Foot, toes Trunk and back	24 18 17 10 9 9
Stevenson et al. (2000)	Community players (all ages)	15.2	Goalkeeper Defender Midfielder Attacker	Not reported	Not specified	-	Not reported	-
Murtaugh (2001)	NCAA female players in practice and matches	0.4/athlete/year	Goalkeeper Defender Midfielder Attacker	14.7 29.9 24.9 30.5	Ball Stick Player Ground	42 36 18 4	Lower limb Head/face Upper limb Back torso	51 34 14 1
Finch et al. (2002)	Community players (all ages)	15.2	Goalkeeper Defender Midfielder Attacker	Not reported	Not reported	-	Ankle Thigh Knee Finger/thumb Lower leg Head/Face Lower back Foot/toes Shoulder Thorax	28.1 30.0 30.5 31.4 18.6 24.8 11.0 11.9 3.8 5.2
Junge et al. (2006)	Olympic Games	21 men /1000hrs 4 women /1000hrs	Goalkeeper Defender Midfielder Attacker	Not reported	Non-contact Contact	38 62	 Head and neck Hand/wrist/finger Knee Ankle Trunk	M W 22 50 6 25 22 0 14 13 8 13
Yard and Comstock (2006)	Paediatric emergency admissions (Males and females 3 – 9 yrs)	-	Goalkeeper Defender Midfielder Attacker	Not reported	 Stick Ball Player Fall	M W 75 44 19 45 4 8 2 18	 Hand and wrist Face Lower leg/foot ankle Upper leg/knee	M W 28 35 24 21 17 20 8 8

Dick et al./ Hootman et al. (2007) Game (G) /Practice (P)	NCAA Not reported for field hockey	3.7 per 1000 AEs / 21.2 in practice, 15.0/1000 AEs competition	Goalkeeper Defender Midfielder Attacker	19.5 23.6 27.6 22.4	Other contact No contact Player contact	G P 59.8 / 26.0 26.3 / 64.0 12.5 / 5.0	Lower extremity Head/neck Upper extremity Trunk/back	G P 43.2 60.2 25.3 8.4 20.7 8.1 7.1 16.2
Rauh et al. (2007)	High school sports	13.3 (initial injury risk ratio)	Goalkeeper Defender Midfielder Attacker	Not reported	Not specified	-	Ankle Head / face Forearm/wrist/hand Knee Lower leg	19.7* 17.8* 13.2* 12.1* 6.8* *new injuries
Rishiraj et al. 2009	21 Canadian female players	70 per 1000 AE	Goalkeeper Defender Midfielder Attacker	10 36 22 32	No contact Surface Player Stick	62 12 12 9	Lower back Ankle/foot Knee Quad Hip flexor Wrist	14 14 13 10 8 8
Sharma et al. (2012)	Elite males (district, state, university, national)	Not specified	Goalkeeper Defender Midfielder Attacker	7.5 37.7 30.6 29.8	Tackling Other Dribbling End furring	44 33 20 3	Face Ankle Knee Shoulder Lower leg Lumbar spine Wrist	17.9 13.5 9.9 8.7 7.5 6.8 6.0
Engebretsen et al. (2013)	Elite players	-	Goalkeeper Defender Midfielder Attacker	Not reported	Not reported	-	Not reported	-
Theilen et al. (2016)	Elite players in tournament matches	48.3 men / match hours 29.1 women / match hours	Goalkeeper Defender Midfielder Attacker	Not reported	Ball Stick Player collision Falling/Tripping Unknown	M W 37 52 25 14 23 12 15 20 0 2	Head/face Hand Trunk abdomen Thigh/knee Calf Ankle Unknown	M W 27 40 19 14 14 0 28 12 13 16 9 18
Furlong and Rolle (2017)	U18 elite players (males and females)	0.98 per match	Goalkeeper Defender Midfielder Attacker	Not reported	Hit by stick/ball (primarily)		Lower limb/torso Upper limb Head and face	15 3 2* (*number reported)
Hollander et al. (2018)	Male and female club players	3.7 / 1000 hours - overall 2.7 / 1000 hrs - practice 9.7 / 1000 hrs - games 4.02 / 1000 hrs - outdoor 3.26 / 1000 hrs - indoor	Goalkeeper Defender Midfielder Attacker	6.9 32.7 28.7 31.7	Noncontact* Contact Not specified	58.3 35.2 6.5	Lower extremity Upper extremity Trunk Head	59.3% 19.4% 9.3% 5.6%

					*injuries to thigh (25.4%), lower leg (14.3%) and trunk (14.3%)			
Delfino Barboza et al. 2018	Dutch elite field hockey players (men and women)	2.5 in training 12.3 in comp per 1000 player hours	Goalkeeper	5	No contact*	43	Thigh	18
			Defender	18	Ball	21	Knee	13
			Midfielder	53	Player	14	Hip/groin/pelvis	12
			Attacker	24	Ground	12	Lower back	10
					Stick	6	Lower leg	10
					Wall/goalpost	4	Foot/toe	8
					(*acute injuries reported)			
Barboza et al. (2019)	Systematic review	0.1 – 90.9 per 1000 hours	Goalkeeper	4 – 19	Non-contact	12 – 64	Lower limb	13 - 77
			Defender	16 – 36	Contact with ball	2 -52	Head	2 – 50
			Midfielder	22 – 37	Contact with stick	9 -27	Upper limb	0 – 44
			Attacker	22 - 37	Contact with player	2 – 45	Trunk	0 -16
					Ground contact	9 - 15		
Rees et al. 2020	Men's recreational	9.4 / 1000 hrs Time loss = 4.0	Goalkeeper	4	Non - contact	66.9	Hamstring 18.6	18.6
			Defender	34.7	Contact - object	23.2	Knee 12.1	12.1
			Midfielder	25.7	Contact player	6.9	Hip/groin 11.8	11.8
			Attacker	35.6				
Cornelissen et al., 2020	Systematic review of recreational field hockey	1.47 per 1000 AE (Youth (timeloss)	Not reported	-	Youth – games	4.9 per 1000 AE's	Lower extremity = highest	
		11.32 per 1000 AE nontimeloss			Adult – games	7.9 per 1000 AE's	Youth knee	0.33 per 1000 AE's
							Youth Head/face/eye	0.66
							Adult hamstring	0.75
		2.2 (nontimeloss)					Adult	0.94
		15.2 timeloss						

*new injury only; #highest in each time bracket; M men; W women

Appendix 2.0 contd

Author /Date	Nature of injuries	%	Severity	%
Fuller et al. 1990 Via Barboza et al.2018	-	-	0-2 days	90
			2+ days	10
Stevenson et al. (2000)	Contusion (only most common listed)	39	Not reported	-
Murtaugh (2001)	Ligament sprain (mostly ankle)	39.7	Not reported	-
	Contusions	17.1		
	Fractures	16.4		
	Wounds	9.4		
	Muscle strains	8.1		
	Concussion	7.7		
Finch et al. (2002)	Muscle strain/tear	53.3	Not reported	-
	Contusion	79.5		
	Ligament sprain/tear	25.7		
	Broken bone	14.3		
	Cut (under 10% not included)	15.2		
Junge et al. (2006)	Contusion	42 (M) 38 (W)	1 – 3 days	50.0
	Laceration/abrasion/blister	19 (M) 25 (W)	4 – 7 days	27.3
	Concussion	(M) 25 (W)	>1 month	9.1
	Sprain	11 (M) 13 (W)		
Yard and Comstock (2006)	Laceration	65.6 (M) 50.6 (W)	Not specified	
	Contusions	22.7 (M) 31.0 (W)		
	Fracture	4.0 (M) 14.0 (W)		
Dick et al./ Hootman et al. (2007)	Ankle sprains	10.0	>10 time-loss days -	15
Games/Practices	Concussion	3.9	game	13
	ACL injuries	1.6	- practice	
Rauh et al. (2007)	Sprains	25.2	<8 days	79.6
	Strains	19.3	8-21 days	13.3
	General	39	>21 days	7.1
	Stress fractures	1.3		
	Fractures	5		
	Neurotrauma	3.3		
	Musculoskeletal	2.4		
		*new injuries		
Rishiraj et al. 2009			<7 days	81
			8-12 days	17
			>21 days	2
Sharma et al. (2012)	Contusion	28.8	Not reported	
	Sprain	13.4		
	Tendinopathy	11.9		
	Hematoma	10.7		
	Bruises	7.9		
	Spasm	7.9		
	Strain	4.8		
	Meniscus	3.4		
	Others	9.5		
Engebretsen et al. (2013)	Not reported	-	>7days Women	2.1
			>7days Men	3.1
Theilen et al. (2016)	Not reported		Not reported	-
Furlong and Rolle (2017)	Contusions	Not reported	Not reported	-
	Fractures			
	Winded			
	Sprains			
Hollander et al. (2018)	Muscle strain	23	Mild	38%
	Contusion	17	Moderate	30.5%
	Others	12	Severe	31.5%
	Other bone injury	10		
	Rupture (tendon/ligament)	8		
	Fracture	7		
	Sprain (ligament)	7		
Delfino Barboza et al 2018	Knee pain*	13	Time loss	(Median reported)
		11	All	0.5

	Back referred hamstring tightness Lumbar pain Stress/overuse thigh injury (*overuse injuries only)	8 8	Acute Overuse Medical Time-loss	1.0 0.0 0.8 2.0
Barboza et al. (2019)	Contusions/haematomas Abrasions/lacerations Sprains Strains Concussion	14 – 64 5 – 51 2 – 37 0 -50 0 - 25	N/A	-
Rees et al. 2020	Muscle strains Pain Contusions	34.7 18 16.4	Fractures Nerve Lacerations Meniscal injuries	32 days lost 22.3 16 16
Cornelissen et al. (2020)	Not reported	-	Not reported	-

Appendix 2.1 Filtering examples (kinematic)

Activity	Author	Specific activity	Filter type	Frequency level
Landing	Kellis et al. (2003)	Drop land	Butterworth (second order, zero phase lag)	Not specified; compared residuals of filtered vs. unfiltered
	Hewett et al. (2005)	Two-foot countermovement jump	Butterworth	Low pass, 9Hz
	Ford, Hewett, and Myer (2007)	Drop vertical-jump reliability	Butterworth (low pass, fourth order)	12Hz
	Stafford (PhD study) (2012)	Jump land	Butterworth (fourth order)	20Hz
	Keeney, Stanhope et al. (2016)	Drop jump	Butterworth (second order, recursive)	12Hz cut-off (low-pass filter)
Hop	Chang et al. (2012)	Hop with(out) knee brace	Butterworth (fourth order)	6Hz
	Van der Haast (2007)	Hop	Butterworth (second order)	9.5Hz
Sidestep	Roewer et al. (2012)	Sidestep with comparison of filtering mechanisms	Butterworth (bidirectional filter)	Low cut-off (10, 12, 15); filtering alters results; knee abduction moment; need to conduct a residual analysis to obtain the appropriate filter level; knee moments here ranged from 24–31 (depending on the filter)
	Kristianlund et al. (2012)	Joint moments from inverse dynamics	Woltring (spline smoothing)	10Hz and 15Hz cut-off
	Pappas et al. (2016)	Sidestep (inverse dynamics)	Not reported	Cut-off frequency of 12Hz
Other	Sinclair, Taylor and Hobbs (2013)	Running (comparison of filtering, as there is a significant difference between frequencies)	Butterworth (fourth order, zero lag)	1, 3, 5, 7, 10, 15, 20, 25Hz; optimal via residual analysis; 25Hz = 99% signal power; 10Hz = 95% signal power
	Zazulak et al. (2007)	Trunk control after weight release	Butterworth (fourth order, dual pass)	8.5Hz
	Yu et al. (1999)	Walking	Residual analysis	Residual analysis not good for determination of optimal cut-off

Appendix 2.2 Filtering examples (kinetic)

Activity	Author	Specific activity	Filter type	Frequency level
Drop jump	Hewett et al. (2005)	Two-foot countermovement jump	Butterworth	50Hz
	Ford, Hewett, and Myer (2007)	Drop vertical jump – reliability	Butterworth (low pass, fourth order)	12Hz (10N = IC)
	Keeney, Stanhope et al. (2016)	Drop jump	Butterworth (second order, recursive)	12Hz
Hop	Van der Haast (2007)	Hop	Butterworth (second order)	9.5Hz
Sidestep	Roewer et al. (2012)	Sidestep with comparison of filtering mechanisms	Butterworth (bidirectional filter)	Filtering alters results, which in this case concerns the knee abduction moment; need to conduct a residual analysis to obtain the appropriate filter level; knee moments here ranged from 24–31 (depending on the filter)
	Kristianlund et al. (2012)	Joint moments from inverse dynamics	Woltring (spline smoothing)	10Hz and 15Hz cut-off 10Hz cut-off (10–10) for both; 15Hz cut-off (15–15) for both 50Hz cut-off (10–50 and 15–50)

	Pappas et al. (2016)	Sidestep – analysis via inverse dynamics	Not reported	12Hz
Other	Zazulak et al. (2007)	Trunk control after weight release	Butterworth (fourth order, dual pass)	8.5Hz

Appendix 3.1 Hockey Injury Questionnaire

Introduction

This questionnaire is to establish the current incidence of non-contact injuries in hockey. The first section asks some background information, the second asks about any injuries in the last 12 months and the third about your current exercise/training practice. Please answer all questions as honestly as possible. All completed questionnaires are anonymous and confidential.

Section 1 – General Information

1. **Gender** Male Female **(Please circle)**

2. **Age** Under 18 18-25 26-30 31-35 36-40 41-45 46-50 51-55 55+
(Please circle)

3. **How many years have you played hockey? (Please circle)**
1 year or less 2-5 years 6-10 11-15 16-20 21+

4. **What position do you predominately play? (Please circle one only)**

Goalkeeper Defence Midfield Attack

5. **How many hours do you play Hockey per week ?** ______________hours

6. **How many weeks do you play during the year?** ______________weeks/year

7. **What standard of play did you predominately play at over the last 12 months?**

Senior International U21 International U18 International National League Division 1 National League Division 2

National League Division 3 League   Regional/Reserve league   District League   Masters only   Ladies Championship

Section 2 Injuries Sustained in Hockey – please recall your injuries over the last season

8. Did you have any injuries caused by contact with Stick and/or ball in the last season   Yes   No

9. Did you have any injuries caused by contact with another player in the last season?   Yes   No

10. Did you have any injuries when there was no contact with another player, stick or ball? Yes **(please go to the next question)** No **(please go to Question 20)**

Please complete questions 11-19 for each injury you have sustained in the last 12 months, only refer to one injury for each set of questions. Additional sheets are provided for each injury at the back of the questionnaire.

11. Which body part was injured?

Foot   Ankle   Calf   Knee,   Quadriceps   Hamstring   Groin   Hips   Lower Back   Upper back   Shoulders   Arm   Hand/Fingers other   Other   (Please state)

12. Which side of the body did it occur on?

Left   Right   Both

13. When did it occur

14. Warm up   Training   Competition – 1st quarter (1st half)   Competition – 2nd quarter (1st half)   Competition – 3rd quarter (2nd half)   Competition – 4th quarter (2nd Half)   Cool down   Other   (Please state)

15. Which part of the season did it occur?

Pre-season August September October November December January February March
April May June July

16. How was the injury caused? (more here)

Slip Fatigue Mistake Self trip Landed Awkwardly Sudden Acceleration Sudden deceleration
Other (please state)

17. What type of injury was it? (Please circle the one that describes the injury)

Bruise Abrasion Fracture Ligament sprain Ligament break Muscle tightness/stiffness Muscle strain
Pulled muscle Muscle tear Dislocation Other (please specify)

18. For how long could you not play hockey?

No time off Missed the next session Missed 1 – 2 weeks Missed 1 – 2 months
Missed 3 – 6 months Missed 12 months +

19. What category of injury is it?

Acute (a problem after a single event) Overuse/Chronic (gradually came on after a lot of use)

20. Is this an injury you have had before or is this a reoccurring injury? First time Reoccurring

21. Have you limited you playing style or techniques used in Hockey to protect your muscles or reduce the chance of injury Yes No
If so, can you give any more information, techniques not used or actions not carried out

22. Did you play indoor hockey in December and January? Yes **(go straight to Qu22)** No **(Please go to the next question)**

23. If you didn't play indoor hockey in December and January, did you do a 2nd pre-season in January before the outdoor season starts?
Yes No

Section 3 All questions in this section refer to your current training/exercise practice

24. Do you have any training/workouts in between training sessions/games? Please circle <u>all</u> that apply
None Stretching Cardiovascular training Muscular Endurance Strength and Conditioning Balance and Stability training
Other (please state)

25. Do you do any of the following in training? Please circle all that apply
None Cardiovascular exercise in training other than playing hockey (long runs) Muscular Endurance exercises (e.g. Multiple sprints)

Strength and conditioning exercises (e.g. Squats, Single leg squats) balance and stability exercises (e.g. the Plank)

24. Who normally leads the warm up/cool down and stretches? Please circle just one

Coach Captain Member of the group with exercise expertise Varies No-one

Someone other than the coach with expertise in Exercise On own

26. Does your coach give you advice on injury reduction?
None Stretching Cardiovascular training Muscular Endurance Strength and Conditioning Balance and Stability training
Other (please state)
26. Do you get advice on injury reduction from anyone else in your club? No Yes If so, please name their role in the club
Thank you for completing the questionnaire

Appendix 3.2 Participant Information Sheet - Questionnaire

“The effects of a specific warm up on movement patterns and injury reduction”

My name is Tom Johnston and I am a post graduate student from the School of Life Sciences at Edinburgh Napier University. I am undertaking a research project for my PhD. The title of my project is:

“The effects of a specific warm up on movement patterns and injury reduction”

This study will investigate if a sports specific warm up can improve movement patterns and reduce the incidence of injury in Hockey.

The findings of the project will be valuable because there is evidence to suggest that injuries can be reduced with a sports specific warm up. The first part of the study will be into the incidence of injury assessed via a questionnaire.

I am looking for volunteers to participate in the project. There are no criteria (e.g. gender, age, or health) for being included or excluded – everyone is welcome to take part.

If you agree to participate in the study, you will be asked to complete the attached questionnaire. The researcher is not aware of any risks associated with completing the questionnaire. Completing the questionnaire should take no longer than 10 minutes. You will be free to withdraw from the study at any stage and you would not have to give a reason. This project will also mean that I will have to read the informed consent and questionnaire.

All data will be kept within the General Data Protection Regulation (GDPR) guidance (Data Protection Act 2018) and anonymised as much as possible. Your name will be replaced with a participant number or a pseudonym, and it will not be possible for you to be identified in any reporting of the data gathered. All data collected will be kept in a secure place (specify in a locked cabinet in locked room) to which only Tom Johnston has access. These will be kept till the end of the examination process, following which all data that could identify you will be destroyed.

The results may be published in a journal or presented at a conference.

If you would like to contact an independent person, who knows about this project but is not involved in it, you are welcome to contact Geraldine Jones. Her contact details are given below. If you have read and understood this information sheet, any questions you had have been answered, and you would like to be a participant in the study, please now see the consent form.

Informed Consent Form

“The effects of a specific warm up on movement patterns and injury reduction”

I have read and understood the information sheet and this consent form. I have had an opportunity to ask questions about my participation ☐

I understand that I am under no obligation to take part in this study ☐

I understand that I have the right to withdraw from this study at any stage without giving any reason ☐

I agree to participate in this study ☐

Name of participant: ________________________________

Signature of participant: ________________________________

Signature of researcher: ____

Date: __________________

Contact details of the researcher

Name of researcher: Tom Johnston

Address:
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Independent Advisor Dr Geraldine Jones
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Appendix 3.3 Validity and Reliability Results - Question Comprehension

	Expert										
Question comprehension	**1**	**2**	**3**	**4**	**5**	**6**	**Total**	**Average**	**Rating**	**Agreement**	**% Agreement**
1	5	4	5	5	5	5	29	4.83	Relevant	6	100
2	5	4	5	5	5	5	29	4.83	Relevant	6	100
3	5	4	5	5	5	5	29	4.83	Relevant	6	100
4	5	3	5	5	5	5	28	4.67	Relevant	5	83.33
5	5	4	5	5	5	5	29	4.83	Relevant	6	100
6	5	4	5	5	5	5	29	4.83	Relevant	6	100
7	2	4	4	5	5	5	25	4.17	Relevant	5	83.33
8	5	4	5	5	5	5	29	4.83	Relevant	6	100
9	3	4	5	5	5	5	27	4.5	Relevant	5	83.33
10	5	4	5	5	5	4	28	4.67	Relevant	6	100
11	5	4	5	5	5	4	28	4.67	Relevant	6	100
12	3	4	5	4	5	4	25	4.17	Relevant	5	83.33
13	4	4	5	4	5	5	27	4.5	Relevant	6	100
14	5	3	5	4	4	4	25	4.17	Relevant	5	83.33
15	4	4	5	5	5	3	26	4.33	Relevant	5	83.33
16	4	4	5	4	5	3	25	4.17	Relevant	5	83.33
17	4	4	5	5	5	5	28	4.67	Relevant	6	100
18	4	4	5	5	5	4	27	4.5	Relevant	6	100
19	4	4	5	5	5	3	26	4.33	Relevant	5	83.33
20	4	4	5	5	5	4	27	4.5	Relevant	6	100
21	4	4	5	4	5	4	26	4.33	Relevant	6	100
Proportion comprehension	19	19	21	21	21	19	120	20	Relevant		93.65
Proportion comprehension(%)	90.48	90.48	100	100	100	90.48	571.43	**95.24**	Relevant		

Question relevance

Question Relevance							**Total**	**Average**	**Rating**	**Agreement (/6)**	**% Agreement**
1	5	4	5	5	5	4	28	4.67	Relevant	6	100
2	4	4	5	5	5	5	28	4.67	Relevant	6	100
3	4	4	5	5	5	5	28	4.67	Relevant	6	100
4	5	4	5	5	5	5	29	4.83	Relevant	6	100
5	5	4	5	5	5	5	29	4.83	Relevant	6	100
6	5	4	5	5	5	5	29	4.83	Relevant	6	100
7	5	4	5	5	5	5	29	4.83	Relevant	6	100
8	5	4	5	5	5	5	29	4.83	Relevant	6	100
9	5	4	5	5	5	5	29	4.83	Relevant	6	100
10	5	4	5	5	5	5	29	4.83	Relevant	6	100
11	5	4	5	4	5	5	28	4.67	Relevant	6	100
12	5	4	5	4	5	5	28	4.67	Relevant	6	100
13	5	4	5	4	5	5	28	4.67	Relevant	6	100
14	5	4	5	5	3	5	27	4.5	Relevant	6	100
15	5	4	5	5	5	4	28	4.67	Relevant	6	100
16	5	4	5	4	5	5	28	4.67	Relevant	6	100
17	5	4	5	4	5	5	28	4.67	Relevant	6	100
18	5	4	5	5	5	5	29	4.67	Relevant	6	100
19	5	4	5	5	5	5	29	4.83	Relevant	6	100
20	5	4	5	4	5	5	28	4.67	Relevant	6	100
21	5	4	5	4	5	5	28	4.67	Relevant	6	100
Proportion Relevant (n)	21	21	21	21	20	21	125	20.83			
Proportion Relevant (%)	100	100	100	100	95.24	100	595.24	**99.21**			

Scale comprehension

Scale comprehension							**Total**	**Average**	**Rating**	**Agreement (/6)**	**% Agreement**
1	5	4	5	5	5	5	29	4.83	Relevant	6	100
2	4	4	5	5	5	5	28	4.67	Relevant	6	100
3	4	4	5	5	5	4	27	4.5	Relevant	6	100
4	5	3	5	5	5	5	28	4.67	Relevant	5	83.33
5	5	4	5	5	5	5	29	4.83	Relevant	6	100
6	5	4	5	5	5	5	29	4.83	Relevant	6	100
7	3	4	5	5	5	5	27	4.5	Relevant	5	83.33
8	5	4	5	5	5	5	29	4.83	Relevant	6	100
9	5	4	5	5	5	5	29	4.83	Relevant	6	100
10	5	4	5	5	5	5	29	4.83	Relevant	6	100
11	5	4	5	5	5	5	29	4.83	Relevant	6	100
12	5	4	5	5	5	5	29	4.83	Relevant	6	100
13	5	4	5	5	5	4	28	4.67	Relevant	6	100
14	5	3	5	5	4	5	27	4.5	Relevant	5	83.33
15	5	4	5	5	5	5	29	4.83	Relevant	6	100
16	5	4	5	5	5	3	27	4.5	Relevant	5	83.33
17	5	4	5	5	5	3	27	4.5	Relevant	5	83.33
18	5	4	5	5	5	4	28	4.67	Relevant	6	100
19	5	4	5	5	5	4	28	4.67	Relevant	6	100
20	5	4	5	5	5	4	28	4.67	Relevant	6	100
21	5	4	5	5	5	4	28	4.67	Relevant	6	100
Comprehension (n)	20	20	21	21	21	19	122	20.33			96.03

Comprehension (%)	95.24	95.29	100	100	100	90.48	580.95	**96.83**			

Scale relevance

Scale relevance							Total	Average	Rating	Agreement (/6)	% Agreement
1	5	4	5	5	5	4	28	4.67	Relevant	**6**	100
2	4	4	5	5	5	5	28	4.67	Relevant	**6**	100
3	4	4	5	5	5	5	28	4.67	Relevant	**6**	100
4	5	4	5	5	5	5	29	4.67	Relevant	**6**	100
5	5	4	5	5	5	2	26	4.33	Relevant	**5**	83.33
6	5	4	5	5	5	4	28	4.67	Relevant	**6**	100
7	3	4	5	5	5	5	27	4.5	Relevant	**5**	83.33
8	5	4	5	5	5	5	29	4.83	Relevant	**6**	100
9	5	4	5	5	5	5	29	4.83	Relevant	**6**	100
10	5	4	5	5	5	5	29	4.83	Relevant	**6**	100
11	5	4	5	5	5	5	29	4.83	Relevant	**6**	100
12	5	4	5	4	5	5	28	4.67	Relevant	**6**	100
13	5	4	5	4	5	4	27	4.5	Relevant	**6**	100
14	5	4	5	5	3	4	26	4.33	Relevant	**5**	83.33
15	5	4	5	4	5	5	28	4.67	Relevant	**6**	100
16	5	4	5	4	5	4	27	4.5	Relevant	**6**	100
17	5	4	5	4	5	4	27	4.5	Relevant	**6**	100
18	5	4	5	5	5	4	28	4.67	Relevant	**6**	100
19	5	4	5	5	5	4	28	4.67	Relevant	**6**	100
20	5	4	5	4	5	5	28	4.67	Relevant	**6**	100

21	5	5	5	4	5	5	29	4.83	Relevant	**6**	100
Proportion relevant (n)	21	21	21	21	20	20	124	20.67			97.62
Proportion relevant (%)	100	100	100	100	95.24	95.24	590.48	**98.41**			

Reliability

Reliability	**Person 1**		**Person 2**		**Person 3**	
	1st	**2nd**	**1st**	**2nd**	**1st**	**2nd**
1	2	2	1	1	2	2
2	2	2	1	2	3	3
3	3	3	3	3	3	3
4	2	2	3	3	3	3
5	8	8	6	10	4	4
6	29	29	26	20	14	18
7	11	11	5	5	9	9
8	7	7	7	7	7	7
9	8	8	8	8	8	8
10	1	1	2	1	1	1
11	2	2	2	2	2	2
12	1	1	2	2	1	1
13	4	4	N/A	N/A	4	4
14	2	2	N/A	N/A	1	1
15	2	2	N/A	N/A	2	8
16	5	5	N/A	N/A	7	7
17	6	6	N/A	N/A	9	9
18	6	7	N/A	N/A	4	4
19	1	1	N/A	N/A	1	3
20	3	3	N/A	N/A	5	5
21	2	2	N/A	N/A	1	2
22	2	2	N/A	N/A	2	2
23	1	1	2	2	1	2
23	1	1	2	2	2	2
23	1	1	2	2	2	2
24	1	1	1	1	2	2
25	0	0	N/A	N/A	1	4
26	2	2	2	2	12	12
26	3	3	12	12	N/A	N/A
26	10	10	3	3	N/A	N/A
26	N/A	N/A	6	6	N/A	N/A
27	1	1	3	3	3	3
28	2	4	2	3	2	2
28	4	4	3	3	3	3
28	5	5	N/A	N/A	4	4
29	1	1	2	2	5	5
30	2	2	1	1	2	4
31	1	1	7	7	2	2

Overall correlation results – Pearson product correlation

	Correlation
Person 1	0.997
Person 2	0.996
Person 3	0.902
Overall Pearson Product correlation	0.965

Appendix 3.4 Participant Recruitment Poster

Volunteers Needed

M/Phil/PhD Research Project

- Incidence of injury in hockey players
- Establish current warm up practice
- Development a warm up to reduce injury and increase movement patterns for hockey

My name is Tom Johnston and I am a MPhil/PhD student at the School of Life Sciences, Edinburgh's Napier University. My study is, initially, to establish the incidence of injury in Hockey.

Participant requirements -:

Complete a questionnaire on hockey injuries after reading the participation information sheet and signing a consent form.

There are no risks associated with this questionnaire.

If interested in participating, please contact me via email on T.Johnston@napier.ac.uk

All data is anonymous and no trace back to the participant can be made. All data will be kept in a locked drawer in a locked room and only the researcher has access the data. The anonymous data maybe published in a journal or presented at a conference.

Once the questionnaire has been collected, it is not possible to withdraw as each one is anonymous.

If you would like to contact an independent person, who knows the project but has no involvement, you are welcome to contact Dr Geraldine Jones, Lecturer in The School of Life Sciences (G.Jones@napier.ac.uk).

Project supervisor – Dr Konstantinos Kaliarntas Lecturer, School of Life Sciences, Edinburgh's Napier University K.Kaliarntas@napier.ac.uk

Director of Studies – Dr Susan Brown Senior Lecturer, School of Life Sciences, Edinburgh's Napier University Su.Brown@napier.ac.uk

Appendix 4.1 Participant Information Sheet – Coach and team Observation

My name is Tom Johnston and I am a post graduate student from the School of Life Sciences at Edinburgh Napier University. I am undertaking a research project for my PhD. The title of my project is:

“The effects of a specific warm up on movement patterns and injury reduction”

This part of the study will be a coach and team observation. The participants are required to carry out their normal duties with their team and the team to prepare for a game as usual. As participants sometimes alter their behaviour whilst being observed, limited information will be given at this point. Consenting coaches and players will be observed by the researcher. Following the warm up, a small questionnaire will be administered to the coach. A full explanation will be provided at the end of the observation. The findings of the project will be valuable because there is evidence to suggest that injuries can be reduced with a good practice.

I am looking for volunteers to participate in the project. There are no criteria (e.g. gender, age, or health) for being included or excluded – everyone is welcome to take part.

If you agree to participate in the study, you and your team will be observed. The researcher is not aware of any risks associated with completing this element of the study. There are no additional requirements of the study. You will be free to withdraw from the study at any stage and you would not have to give a reason. This project will also mean that I will have to read the informed consent and questionnaire.

All data will be anonymised as much as possible. Your name will be replaced with a participant number or a pseudonym, and it will not be possible for you to be identified in any reporting of the data gathered. All data collected will be kept in a secure place (specify in a locked cabinet in locked room) to which only Tom Johnston has access. These will be kept till the end of the examination process, following which all data that could identify you will be destroyed.

The results may be published in a journal or presented at a conference.

If you would like to contact an independent person, who knows about this project but is not involved in it, you are welcome to contact Dr. Geraldine Jones. Her contact details are given below.

If you have read and understood this information sheet, any questions you had have been answered, and you would like to be a participant in the study, please now see the consent form.

Informed Consent Form

“The effects of a specific warm up on movement patterns and injury reduction”

I have read and understood the information sheet and this consent form. I have had an opportunity to ask questions about my participation. ☐

I understand that I am under no obligation to take part in this study ☐

I understand that I have the right to withdraw from this study at any stage without giving any reason. ☐

I agree to participate in this study. ☐

Name of Coach/player: ______________________________

Signature of Coach/player: ______________________________

Signature of researcher: ______________________________

Date: ____________________

Contact details of the researcher

Name of researcher: Tom Johnston

Address: 2.B.48
School of Life Sciences,
Faculty of Life, Health and Social Sciences,
Edinburgh Napier University
Sighthill Campus
Sighthill Court,
Edinburgh
EH11 4BN

Email T.Johnston@napier.ac.uk

Supervisor Dr Konstantinos Kaliarntas
Email K.Kaliarntas@napier.ac.uk

Independent Advisor Dr Geraldine Jones Email
Email G.Jones@napier.ac.uk

Date :

Name of player:______________________ Signature of player:___________________

Name of player:______________________ Signature of player:___________________

Name of player:______________________ Signature of player:__________________

Name of player:______________________ Signature of player:__________________

Name of player:______________________ Signature of player:__________________

Name of player:______________________ Signature of player:__________________

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Name of player:______________________ Signature of player:__________________

Name of player:______________________ Signature of player:__________________

Name of player:______________________ Signature of player:__________________

Name of player:______________________ Signature of player:__________________

Name of player:______________________ Signature of player:__________________

Signature of researcher: ____________________Date: _________________

Contact details of the researcher

Name of researcher: Tom Johnston

Address: 2.B.48

School of Life Sciences,

Faculty of Life, Health and Social Sciences,

Edinburgh Napier University

Sighthill Campus
Sighthill Court,

Edinburgh

EH11 4BN

Email T.Johnston@napier.ac.uk

Supervisor Dr Konstantinos Kaliarntas

Email K.Kaliarntas@napier.ac.uk

Independent Advisor Dr Geraldine Jones

Email G.Jones@napier.ac.uk

Appendix 4.2 Hockey Warm Up Observation Sheet

Data Observations - Warm-up in field hockey

Team: **Start time:**
Date: **Finish time:**
Duration:

Number	Time	Action	Notes/how many	Number	Time	Action	Notes/how many
1	00:00-00:30			21	09:31-10:00		
2	00:31-01:00			22	10:01-10:30		
3	01:01-01:30			23	10:31-11:00		
4	01:31-02:00			24	11:01-11:30		
5	02:01-02:30			25	11:31-12:00		
6	02:31-03:00			26	12:01-12:30		
7	03:01-03:30			27	12:31-13:00		
8	03:31-04:00			28	13:01-13:30		
9	04:01-04:30			29	13:31-14:00		
10	04:31-05:00			30	14:01-14:30		
11	05:01-05:30			31	14:31-15:00		
12	05:31-06:00			32	15:01-15:30		
13	06:01-06:30			33	15:31-16:00		
14	06:31-07:00			34	16:01-16:30		
15	07:01-07:30			35	16:31-17:00		
16	07:31-08:00			36	17:01-17:30		
17	08:01-08:30			37	17:31-18:00		
18	08:31-09:00			38	18:01-18:30		
19	09:01-09:30			39	18:31-19:00		
20	09:31-10:00			40	19:01-19:30		

Data Observations 'Warm-up in field hockey
Team: **Start time:**
Date: **Finish time:**
Duration:

Number	Time	Action	Notes	Number	Time	Action	Notes
41	19:31-20:00			61	29:30-30:00		
42	20:01-20:30			62	30:01-30:30		
43	20:31-21:00			63	30:01-30:30		
44	21:01-21:30			64	30:31-31:00		
45	21:31-22:00			65	31:01-31:30		
46	22:01-22:30			66	31:31-32:00		
47	22:31-23:00			67	32:01-32:30		
48	23:01-23:30			68	32:31-33:00		
49	23:31-24:00			69	33:01-33:30		
50	24:01-24:30			70	33:31-34:00		
51	24:31 25:00			71	34:01-34:30		
52	25:01-25:30			72	34:31-35:00		
53	25:31-26:00			73	35:01-35:30		
54	26:01-26:30			74	35:31-36:00		
55	26:31-27:00			75	36:01-36:30		
56	27:01-27:30			76	36:31-37:00		
57	27:31-28:00			77	37:01-37:30		
58	28:01-28:30			78	37:31-38:00		
59	28:31-29:00			79	38:01-38:30		
60	29:01-29:30			80	38:31-39:00		

Appendix 4.3 Coach Warm Up Questionnaire

Coach warm up questionnaire

1. **Have you, as the coach, prescribed the warm up for your team?** Yes (Please go to Question 4) No (Please go to Question 2)

2. **If no, who has developed the warm up**

   No prescribed warm up Captain Player who has exercise expertise Assistant coach

   The leader keeps changing Other (please specify)

3. **If no, what was the reason for another person developing the warm up?** (Please specify) If you answer this question, this is your final question.

4. **If yes, what is your desired outcome from the warm up?** (Please list all intentions)

5. **If yes, did the players complete the warm up you prescribed?** Yes No

6. **If no, which element of the warm up did the players miss out?** (Please circle all that apply)

   Pulse raiser Dynamic stretches Proprioceptive exercises Small-sided activities Sports specific movements

   On pitch static skills On pitch dynamic skills Position specific activities

   No missed activities just shorter time No missed activities, less intense

Other please specify -

____

____

____

7. **If no to Question 5, why did they not do the warm up as prescribed?**
   Please include all reasons here

8. **If you, as the coach, have prescribed the warm up exercises, how did you develop the warm up / get the information for the warm up from? (Please circle all that apply)**

   Exercises you have always done
   Coach education courses
   Sports coach UK workshops
   Copying other coaches
   Other Strength and conditioning courses (Please specify)
   Informal discussions with exercise professionals
   Informed by players with exercise expertise
   Developed with exercises that players like
   Other (please specify)

9. **If you would change anything about your team's warm up, what would you change?**

   Pulse raiser
   Dynamic Stretches
   Proprioceptive exercises
   Static on pitch skill rehearsal
   Dynamic skills rehearsal
   Injury prevention exercises
   Time on each activity – more / less (Please circle)
   Greater concentration on each activity (increase the quality)
   Greater intensity on most activities

Adding an aspect of a warm up (If yes, please specify)__________________

Position specific activity (please state which position and skill) -

____

____

____

____

Coach Profile

10. Gender Male Female **(Please circle)**

11. Age 18-25 26-30 31-35 36-40 41-45 46-50 51-55 55+ **(Please circle)**

12. How many years have you coached hockey? (Please circle)

1 year or less 2-5 years 6-10 11-15 16-20 21+

13. What is the highest level of coaching qualification to you hold (Please circle one only)

None Scottish Hockey Leaders UKCC Level 1 (or equivalent) UKCC Level 2 (or equivalent) UKCC Level 3 (or equivalent)

A higher qualification than UKCC Level 3

14. How many hours do you coach Hockey (training and games) per week ? ______________hours

15. How many weeks do you coach during the year? ______________weeks/year

16. What standard of play did you predominately coach at?

Senior International
U21 International
U18 International
National League Division 1
National League Division 2

National League Division 3
Regional/Reserve league
District League
Masters only
Ladies Championship League

Thank you for completing the questionnaire

Appendix 4.4 Study 2 Reliability Results

30 sec interval	Observation 1a	Observation 1b	Observation 2a	Observation 2b	Observation 3a	Observation 3b	Ramp Agree 1 - 2	Ramp Agree 2 - 3	Ramp Agree 1- 3	Ramp Agree 1, 2, 3
1	1	1	1	5	1	5	Yes	Yes	Yes	Yes
2	1	5	1	5	1	5	Yes	Yes	Yes	Yes
3	1	5	1	5	1	5	Yes	Yes	Yes	Yes
4	1	5	1	5	1	5	No	Yes	Yes	Yes
5	2	5	2	5	2	5	Yes	Yes	Yes	Yes
6	2	5	2	5	2	5	Yes	Yes	Yes	Yes
7	2	5	2	5	2	5	Yes	Yes	Yes	Yes
8	2	5	2	5	2	5	Yes	Yes	Yes	Yes
9	2	5	2	5	2	5	Yes	Yes	Yes	Yes
10	2	5	2	5	2	5	Yes	Yes	Yes	Yes
11	2	5	2	5	2	5	Yes	Yes	Yes	Yes
12	4	5	4	5	4	5	Yes	Yes	Yes	Yes
13	3	5	3	5	3	5	Yes	Yes	Yes	Yes
14	2	5	2	5	2	5	Yes	Yes	Yes	Yes
15	2	5	2	5	2	5	Yes	Yes	Yes	Yes
16	2	5	3	5	2	5	No	No	Yes	No
17	3	5	3	5	3	5	Yes	Yes	Yes	Yes
18	3	5	3	5	3	5	Yes	Yes	Yes	Yes
19	4	4	4	4	4	4	Yes	Yes	Yes	Yes
20	4	4	4	4	4	4	Yes	Yes	Yes	Yes
21	4	4	4	4	4	4	Yes	Yes	Yes	Yes
22	4	4	4	4	4	4	Yes	Yes	Yes	Yes
23	4	4	4	4	4	4	Yes	Yes	Yes	Yes
24	2	6	2	6	2	6	Yes	Yes	Yes	Yes
25	2	6	2	6	2	6	Yes	Yes	Yes	Yes

26	2	6	2	6	2	6	Yes	Yes	Yes	Yes
27	2	6	2	6	2	6	Yes	Yes	Yes	Yes
28	2	6	2	6	2	6	Yes	Yes	Yes	Yes
29	2	6	2	6	2	6	Yes	Yes	Yes	Yes
30	2	6	2	6	1	6	Yes	No	Yes	No
31	1	6	1	6	1	6	Yes	Yes	Yes	Yes
32	1	6	1	6	1	6	Yes	Yes	Yes	Yes
33	1	6	1	6	1	6	Yes	Yes	Yes	Yes
34	END	END	END	END	END	END	93.9	93.9	97.0	93.9

Appendix 4.4 Study 2 Reliability Results (RAMP) (contd…)

Warm up content	**Comparison**	**Pearson Product (Exact)**	**Rounded**
RAMP	Live vs 2	0.985	0.99
RAMP	Live vs 3	0.985	0.99
RAMP	2 v 3	0.972	0.97
RAMP	1 vs 2 vs 3	0.985	0.99

Study 2 reliability results (warm up – skill rehearsal)

	Comparison			
Warm up Content	1 vs 2 (%)	1 vs 3 (%)	2 v 3 (%)	1 vs 2 vs 3 (%)
Warm up	100	100	100	100
Skill Rehearsal	100	100	100	100

Appendix 4.5 Coding Sheet

Activity	**Code**		**Activity**	**Code**
Walking	W		Static passing	Sp
Jogging	J		Dynamic passing	Dp
Striding	Str		Tackling practice	T
Sprinting	Spr		Small Sided Game	SSG
Backwards running	BkR		Passing weave	Pw
Standing Still	StS		Penalty corners	Pc
High Knees	HK		1-on-1 skills	1v1
High heels	HH		2-on-1 skills	2v1
Sidestep	SS		Pass and shoot	P&S
Skipping	Sk		Possession Game	PG
Carioca /grapevine	CG		Individual activity	IA
Static stretching	SS		Other – pulse raise	OPR
Dynamic Stretching	DS		Other - Stretching	OS
Neuromuscular training	NMT		Other – Skill Rehearsal	OSR

Appendix 5.1 Participant Information Sheet – Intervention Study

“The effects of a specific warm-up on movement patterns and injury reduction”

My name is Tom Johnston and I am a postgraduate student from the School of Life Sciences at Edinburgh Napier University. I am undertaking a research project for my PhD. The title of my project is:

“The effects of a specific warm-up on movement patterns and injury reduction”

This study will investigate if a sports-specific warm-up can improve movement patterns and reduce the incidence of injury in Hockey. The findings of the project will be valuable because there is evidence to suggest that injuries can be reduced with a sports-specific warm-up.

I am looking for volunteers to participate in the project. All volunteers to be adults, with 1 year of hockey playing experience and injury-free for 3 months.

If you agree to participate in the study, you will be asked to complete to complete a Physical Activity Readiness Questionnaire (PAR-Q) and sign an Informed Consent form prior to the intervention. The Physical Activity Readiness Questionnaire (PAR-Q) assesses confirms that you are able to take part in the study. Each participant will be asked to complete the warm-up prior to each training session and game for an 8 week period instead of your ‘normal’ warm-up. This will last between 15 and 20 minutes each time. There is evidence to suggest that the more times you complete the exercises in the intervention, the fewer injuries will be sustained. In this project, the researcher recommends you complete the warm up at least twice per week during the intervention period. Or the participants will be in the control group (being tested and performing your normal warm up and then being re-tested. The researcher is aware that this intervention is active and will involve movements that you may not be used to and may feel some muscle fatigue and soreness. However, the warm up has been developed with the evidence in the literature so therefore this should be minimal. Before and after the intervention begins, each participant is required to attend the Sport Science laboratory at the Sighthill Campus of Edinburgh’s Napier University. The testing session will last 2 hours (approx.), have reflective markers placed on the body to allow for the detection of movement of the body, and Electromygraphy (EMG) units placed on leg muscles to allow for muscle activity to be measured. The reflective markers are small shiny balls that are secured to the body and the Electromyography (EMG) units are like small plastic match boxes secured above the muscles of the leg and detects muscle contractions below. The reflective markers will be placed on body on skin or on clothes. Both the EMG and reflective markers are secured using an adhesive, if you are allergic, please indicate this on the PAR-Q form. During the testing you will be asked to perform a sagittal plane hop, hop and twist and unanticipated sidecut.

Participation in this study is voluntary and unfortunately travel expenses cannot be reimbursed.

You will be free to withdraw from the study at any stage and you would not have to give a reason.

All data will be anonymised as much as possible. Your name will be replaced with a participant number or a pseudonym, and it will not be possible for you to be identified in any reporting of the data gathered. All data collected will be kept in a secure place (specifically in a locked cabinet in locked room) to which only the researcher has access. These will be kept till the end of the examination process, following which all data that could identify you will be destroyed.

The results may be published in a journal or presented at a conference. There will be no reference to participants by name, each participant will be referred by a pseudonym and it will not be possible to be identified in any publication.

If you would like to contact an independent person, who knows about this project but is not involved in it, you are welcome to contact Jay Mackinnon. Her contact details are given below.

If you have read and understood this information sheet, any questions you had have been answered, and you would like to be a participant in the study, please now complete the consent form.

Contact details of the researcher

Name of researcher: Tom Johnston

Address: 1.B.13

Faculty of Life, Health and Social Sciences,

Edinburgh Napier University

Sighthill Campus,
Sighthill Court,

Edinburgh

EH11 4BN

Email T.Johnston@napier.ac.uk

Director of Studies Dr Konstantinos Kaliarntas

Email K.Kaliarntas@napier.ac.uk

Independent Advisor Jay MacKinnon

Email J.McKinnon@napier.ac.uk

Appendix 5.11 Consent Form for Participation in Physical Activities

For your participation in a Sport and Exercise Science activity, you are asked to complete the form below regarding your current health. In accordance with the Data Protection Act 1998 all the information you provide will be held securely and treated in the strictest confidence. This information will be viewed only, not be shared with anyone else unless this is: with your agreement, required by law or to protect your vital interests.

Name: ....
Date of Birth…………….
Hockey Club/league playing in ....
Playing experience (in years)…………………………………………
Height: ……………….(m)
Weight: ……………….(kg)

GENERAL HEALTH INFORMATION

Look carefully at the following list and tick which symptoms apply to you. If you feel necessary please discuss with the experimenter whether you should exercise.

Allergies	☐	Arthritis/swollen, stiff or painful joints	☐
Asthma	☐	Chest Pains / Discomfort	☐
Cold or flu like symptoms (in the past week)	☐	Diabetes	☐
Epilepsy	☐	Heart or Lung trouble	☐
High Blood pressure	☐	Orthopaedic problems	☐
Palpitations	☐	Shortness of breath	☐
Other	☐	None of the above	☐

Have you been injured in the last 3 months Yes ☐ No ☐

If yes, please give details in the space below.

PLEASE READ THE FOLLOWING CAREFULLY:

If you suffer any unusual or any unexpected symptoms during the activity, **please stop immediately**. If you experience any such feelings once the experiment/test period is over, please consult the experimenter or, if they occur after class has finished, please consult your own doctor.

DECLARATION

I,………………………………………………………………………., volunteer to be participant in Sport and Exercise Science experiments.

I have read and understood the experiment descriptor provided and the experimenter has explained to my satisfaction the purpose of the experiment and possible risks involved.

I understand that it is my responsibility to advise the experimenter of any changes in my health during the course of the study.

I understand that I may withdraw from the activity at any time and that I am under no obligation to give reasons for withdrawal. Furthermore, I understand that my choice to participate in this experiment will neither be detrimental to nor further my position in any way.

Informed Consent Form

“The effects of a specific warm up on movement patterns and injury reduction”

I have read and understood the information sheet and this consent form. I have had an opportunity to ask questions about my participation ☐

I understand that I am under no obligation to take part in this study ☐

I understand that I have the right to withdraw from this study at any stage without giving any reason ☐

I agree to participate in this study ☐

Name of participant: ______________________________________

Signature of participant: _______________________________________

Signature of researcher: _______________________________________

Date: __________________

Appendix 5.2 Intervention Exercises and Instructions

Part	**Exercise**	**Reps/time / distance**	**Technique points/ Principle muscle activated**
Part A Pulse raiser	Russian Walk	5 metres	Walking on heels, straight legs, upright posture. Arms out for balance.
Mobilisation	Jog with plantar flexion	10 m	Jog with upright posture arms swing as normal, as feet landing dorsi flex so land on balls of feet then heel down and repeat with other leg. Arms out for balance.
Running muscle activation running technique	Foot stamping	5 reps on each side	Hold on to support (player, fence) upright posture, flex standing leg. Active leg – (Phase 1) knee up to parallel to floor knee fully flexed under hips, (Phase 2) full extension, increasingly quickly (Phase 3) extend knee and stamp foot to the floor. Non-support arm Arms out for balance. Reduce or release support arm to increase balance requirements. Focus on reducing/eliminating hip adduction.
	'Ready position'	1	Feet shoulder width apart, trunk and knees comfortably bent, shoulders back, eyes looking forward. Participants educated on low risk landing position. Feedback provided.
	Deep squats (or as deep as possible)	10	Flex knees and squat until just past thighs parallel to the floor – butt touch a box if it was there.
	Arabesque	X 3 each leg	Start with hands on hips with support leg on the ground and slight knee flexion. With other that is straight, lift leg up to the back and trunk leans forward and bring hands out to the side. Then return to start position. A slow movement
	Whole running action forwards	X 20m	Upright posture, knee to parallel during mid swing, active plantar flexion during foot contact.
(pivot into)	Jog backwards	X 20m	Drive backwards.

	Mini Skip into gradual increase of distance 2nd time round skip for height	20m	Hop to mini step and increasingly forward propulsion. Increase arm action to aid larger hop.
	Side shuffle (Left leg lead for 10m then right leg lead for 10m)	20m	In crouch position (ready position in hockey) – trunk slightly flexed, knees slightly bend and shuffle sideways.
	Repeat x2 last 4		
Part B Hip Mobility	Over Hurdle (trial leg)	X 5	Plant support leg next to ‘hurdle’. Bring active leg back (extend hips) and flex knee. Circumduction of femur. Opposite arm out to the side to reduce trunk twist. Upright stance to reduce anterior and lateral pelvic tilt.
Motor control	Over hurdle backwards	X 5	Plant support leg next to ‘hurdle’. Lift knee up to the front parallel to the floor and raise foot to the side and circumduct femur backwards. Trunk – remain upright and opposite arm to active, out to the side to reduce pelvis /trunk movement.
Posture NMT	Over sideways	X 5	Step over hurdles, when first leg lands other leg begins action. Support leg is near hurdle. Lead leg lifts vertically to parallel to the ground with knee flexion, then abducts with slight weight transfer and lands on the other side of the hurdle.
	Under hurdle (squat under hurdle)	X 5	A lateral squat action. Bend primarily at the knee with heels on the ground and trunk as upright as possible.
	Repeat with other leg lead		
	Lunge complex – lunge forward, forward diagonal lunge and backward	1 of each on each side and repeat	Upright posture with hands on hips, lift thigh (as if over a hurdle) step forward, flex knees til the back knee almost ouches the ground and return. As step, lift arms to the side to avoid pelvic tilt.
	Lunge complex with rotation	1 of each on each side and repeat	One of lunge each and first time rotate into bent leg, second time rotate away from bent leg.

Part C Activation	Caterpillar Walk	X5	Start in press up position. Walk feet into hands as far as possible – keep back and legs straight and then walk hands out to return to press up position and pause 3 secs.
Mobility Core activation	Bear walk	10 steps (5 movements forward each side)	On all fours with knees off the ground, move opposite hands and feet forward. Hips just above should height.
	Lizard walk	6 steps (3 movements forward each side)	On all fours with knees off the ground, move opposite hands and feet forward. Shoulders and hips close to the ground
	Bear walk unanticipated	10 steps (5 movements forward each side)	Shoulder girdle activation, trunk stabilisation rectus abdominals, erector spinae, internal/external oblique. Leg flexors and extensors used in a more minor way. In pairs, face each other and follow the leader and swop over.
	Lizard walk diagonal	6 steps (3 movements forward each side)	On all fours with knees off the ground, move opposite hands and feet forward. Shoulders and hips close to the ground. In pairs, face each other and follow the leader and swop over.
After each primal movement	Crab - like a pelvic bridge. On both legs	3	Turnover on to face the sky, on all fours push hips to form a table top.

Part D	Balance on one leg with ball throw	X10 total	Balance on one leg with leg slightly flexed. Throw hockey ball to partner at a variety of height and sides. Then change legs
(straight into)	Hopping on one leg	x10 total	Hopping on one leg with leg slightly flexed. Throw hockey ball to partner at a variety of height and sides. Then change legs.
	Multi directional hopping (figure of 8)	X2 figures on each leg	Start on one leg and hop diagonally left, then laterally right, diagonally backwards left and laterally right. Repeat in other direction and other leg.
	Forward hop and hold	8 on each leg	Hop forward, land using ‘ready’ position and hold, then repeat x 8 and repeat on other leg. Single leg balance
	Diagonal bound with secure landing	5 steps on each leg, 10 total	Push off with a slightly flexed torso and land on opposite foot, as land slight flex knees. Trunk should remain slightly flexed. Avoid trunk collapsing (i.e. uncontrolled trunk flexion) and internal rotation of the knee.
(straight into from bounding)	2 foot jump	16 jumps – 4 to each place	Double legged jumps with upright posture with a little trunk flexion but keep shoulders back and look forward. Jump forwards, backwards and to each side and back to centre each time.
	Tuck jumps	10	Squat down and jump up and tuck knees into chest then land into ready position using a soft-landing strategy.
	Broad jumps	10	2 footed forward jump and land. Land without valgus motion and soft-landing strategy.
	Single leg squat	5 per leg (alternate with partner)	One player hold stick for partner to hold on to. One leg flex as much as possible while other is off the ground and out in front. Avoid knee internally rotating.
	Nordic hamstring	3 x 2	Neal with partner holding ankles. Lean forward slowly until fall to floor. Hands out ready to catch the body. After 3, swop with partner x 2

Potentiation NMT Agility	Double taps	10m x 2	Slightly faster than above - both feet touch per space. Increase of contraction speed. Upright posture with high knee lift.
	Forward and back (3 x forward and one back)	10m x 2	High knee lift and upright posture, shoulders back. Forward over 3 cones and backwards over 1 cone and repeat going forward x 5.
	Double taps - lateral	10m x 2	Lateral agility
	Hop over	10m x 2	1 leg per 10m.
Part E Potentiation, Unanticipated move	Sprint 15m x 3	15m x 2	Sprint, maximal activity with upright posture. Implementing running technique earlier.
(pivot into)	Sprint backwards	15m x 2	After sprint forwards, pivot and sprint backwards in a straight line. similar muscles but a change of emphasis.
	Run and sudden stop	5m x 2	Coach or partner says stop to player who is running to develop breaking patterns. Maintain upright trunk and avoid postural sway and uncontrolled trunk flexion.
	Run and cut	15m x 2 approx.	Diagonal run and change direction, 3 cuts to each side. Avoid femur internal rotation during cutting action.
	Run and cut unanticipated	2 unplanned cuts	Run forwards and cut to a direction given by coach/partner x 2 (doesn’t have to be equal). Biomechanics – flex knee, avoid internal rotation of femur.
	Continuous tig	1 min	A tagger chases another player and touches on shoulder region to transfer tag to another player. Previous tagger becomes a players and repeat.

Total time – 18 mins

Appendix 5.3 Study 3 Coaching Points

Exercise	**Internal coaching points**	**External coaching points**
Russian walk	Walk on heels	Like a Russian soldier
Plantar flexion jog	Quite straight legs, slap feet on ground	Running on toes
Foot stamping	Foot up round and down	Like a horse stamping on the ground. Like a piston
'Ready position'	Semi squat, flex trunk and knees, knees over ankles	Toilet seat position
Deep squats	Squat as low as possible, knees over ankles and trunk as upright as possible, heels on the ground	Squat like a frog
Arabesque	Balance on one leg and left other leg back and tilt forward to touch hand on the ground	Pivot round hips like weighting scales
Whole running action	Upright trunk, hips, knees and ankles all aligned	Legs like pistons on a train
Skip – increase in height	Jump high, land toe to heel, drive up as high as possible	Increasingly reach for the sky / spring up
Skip increase in distance	Drive forward with each leg with increasing force, hips, knees and ankles aligned	Spring forward, strong trunk
Over hurdle – trial leg	Trail leg – up and over the 'hurdle', standing leg still and trunk upright	Draw big Circles with the knee of trail leg - forwards
Over hurdle -backwards	Trail leg – up and over the 'hurdle', standing leg still and trunk upright	Draw big Circles with the knee of trail leg - backwards
Over – sideways	Both legs up and over hurdle. Trunk upright and still.	High sideways marching action
Under hurdle - sideways	Step foot through the hurdle, squat down and move under then stand up	Like limbo dancing under a bar

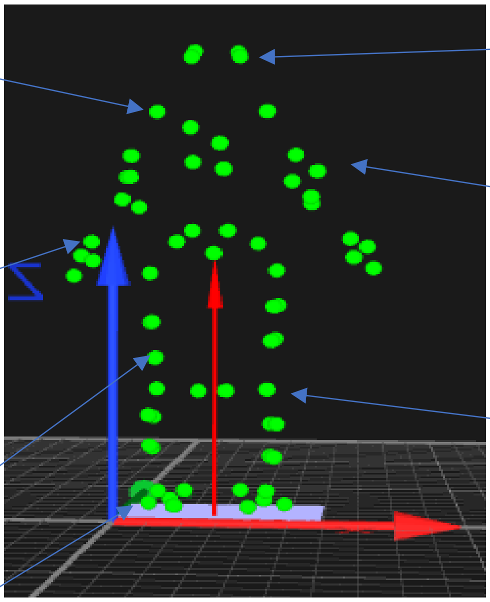
Lunge – all directions	Step forward, knees over ankles, limited trunk movement and push back in all directions	Lunge like you are preparing for sweep pass in hockey
Lunge with rotation	As above but add in rotate to both	Like a hitting or sweeping action in hockey
Caterpillar walk	Walk hands out to flatten body, walk feet in to bend body	Like the hungry caterpillar
Bear walk	Opposite arms and legs, hips and shoulders almost level trunk doesn't rotate	Like a bear [walk] without the waddle
Lizard walk	Lift up trunk to move limbs. Knees to elbows on same side. Lower the body as near knee/elbow contact	Walk like a lizard stalking some prey
Bear walk (unanticipated)	As above with partner leading direction (swop over)	Like a bear [walk] without the waddle, partner leads the direction
Lizard diagonal	As above	
Crab bridge	Face the ceiling, push hips up so flat from shoulders to knees	Make a table top with shoulders, hips and knees
Balance on one leg	Keep still and engage core	Still like a stork with strong trunk
Hopping on the spot	Toe landing to heel touch, knees over ankles and small trunk flex	Bouncy like a kangaroo/bunny
Hopping figure of 8	Toe landing to heel touch, knees over ankles and small trunk flex	Bouncy like a kangaroo/bunny
Forward hop and hold	Toe landing to heel touch, knees over ankles and small trunk flex	Soft landing / land like a butterfly
Diagonal bound	Toe landing to heel touch, knees over ankles and small trunk flex. Secure landing.	Soft landing / land like a butterfly
2 footed jumps – forwards backwards/side to side	Toe landing to heel touch, knees over ankles and small trunk flex	Bouncy kangaroo
Broad jumps	Bend knees on landing, knees over ankles some trunk bend	Soft, smooth landing. Land like a feather

Single leg squats	Partner assisted, low as possible and up, knee over ankle and trunk upright	Fold at joints on way down and unfold on way up
Nordic hamstrings	Lower slowly to floor	
Double taps	Tap each leg into each space in the agility ladder	Fast feet
Forward and back	3 steps forward and 1 back	
Double taps lateral	Facing sideways. Each foot into the ladder space then backwards, sideways forwards, sideways in a castle turret shape	Fast feet like a crazy crab
Hop over	Land with knee bend on some trunk	Soft knees and strong trunk
Sprint 15m x3	Trunk upright	Like Michael Johnson
Sprint backwards	Push off with toes and active hip extension	
Run and stop	As stop bend at knee and trunk a little	Emergency stop
Run and cut – anticipated/unanticipated	Run forward and cut to side, push with opposite leg to direction of movement lean to new direction of travel. Knee over ankle, trunk lean to new direction of travel	One legged ski jump to side
Continuous tig	Match pace	Just like in the playground at primary school

Appendix 5.4 Marker Set used in this study

Marker set in Qualysis Track Manager (QTM)®

Posterior view



2 markers on the acromion.

4 markers on a head band.

3 markers to track the upper arm.

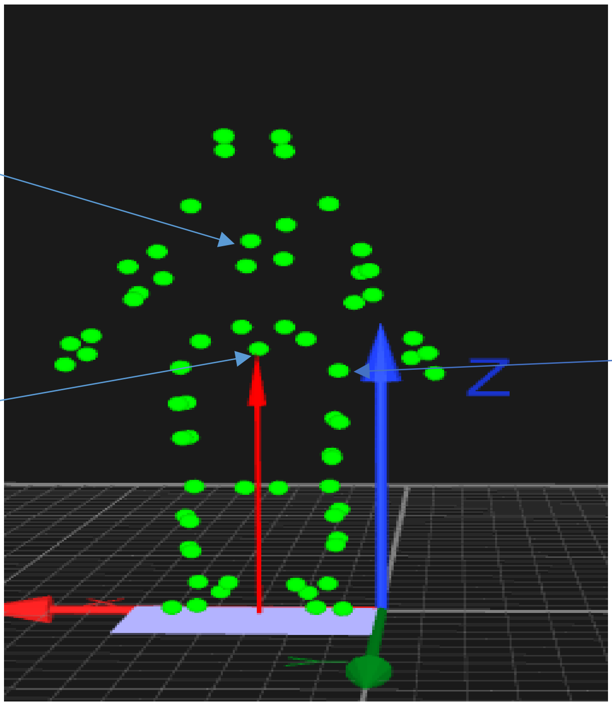
6 markers to track lower arm, wrist and hand

6 (4 in a cluster) markers to track upper leg to knee.

8 markers (4 in a cluster) to form and track the lower leg from knee to ankle.

5 markers to form and track the ankle and foot.

Anterior view



4 markers on a back cluster

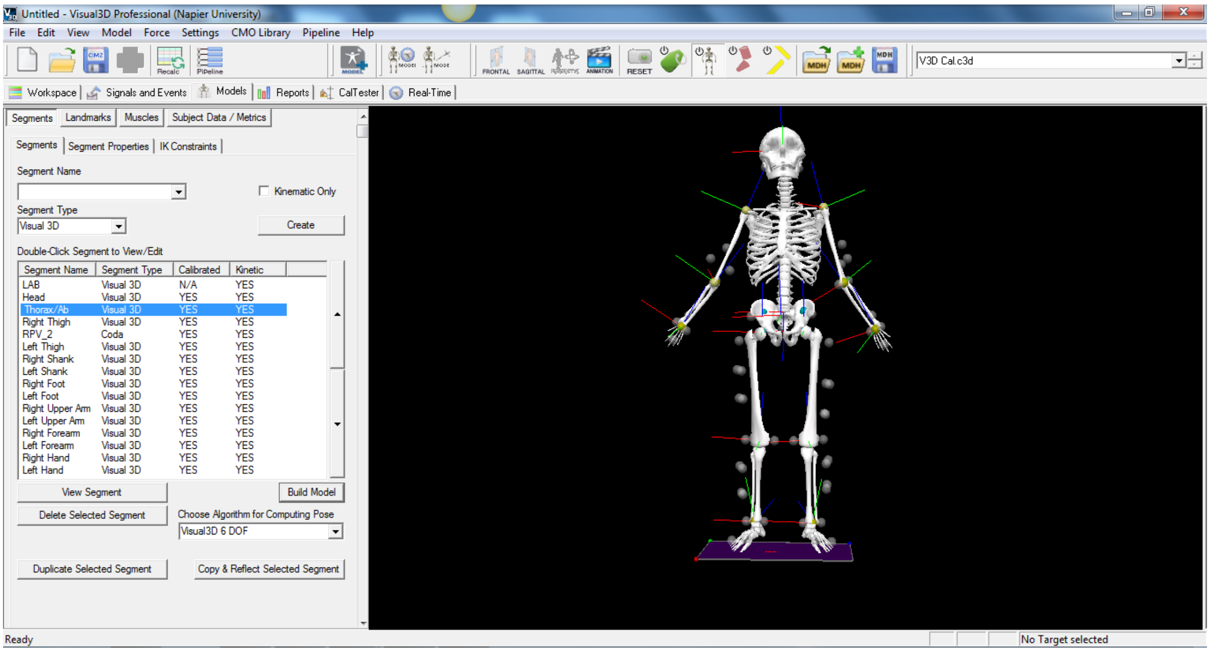
Sacral marker to form the pelvis (in part).

7 markers forming and tracking the pelvis and Greater trochanter.

Appendix 5.5 View of Markers in Visual 3D

Anterior View

The figures below show the markers used and how this forms the skeleton in Visual 3D.



Segment Name

☐ Kinematic Only

Segment Type: Visual 3D

Double-Click Segment to View/Edit

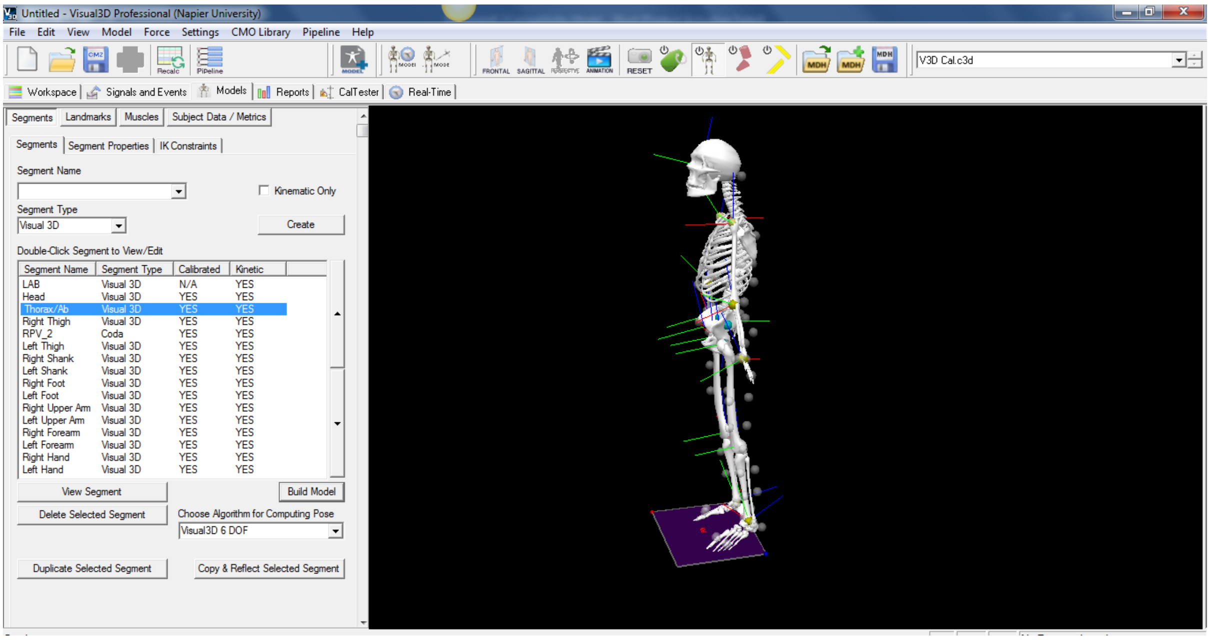
Segment Name	Segment Type	Calibrated	Kinetic
LAB	Visual 3D	N/A	YES
Head	Visual 3D	YES	YES
Thorax/Ab	Visual 3D	YES	YES
Right Thigh	Visual 3D	YES	YES
RPV_2	Coda	YES	YES
Left Thigh	Visual 3D	YES	YES
Right Shank	Visual 3D	YES	YES
Left Shank	Visual 3D	YES	YES
Right Foot	Visual 3D	YES	YES
Left Foot	Visual 3D	YES	YES
Right Upper Arm	Visual 3D	YES	YES
Left Upper Arm	Visual 3D	YES	YES
Right Forearm	Visual 3D	YES	YES
Left Forearm	Visual 3D	YES	YES
Right Hand	Visual 3D	YES	YES
Left Hand	Visual 3D	YES	YES

Choose Algorithm for Computing Pose: Visual3D 6 DOF

Ready

No Target selected

View of Markers in Visual 3D – Lateral View



Segment Name

☐ Kinematic Only

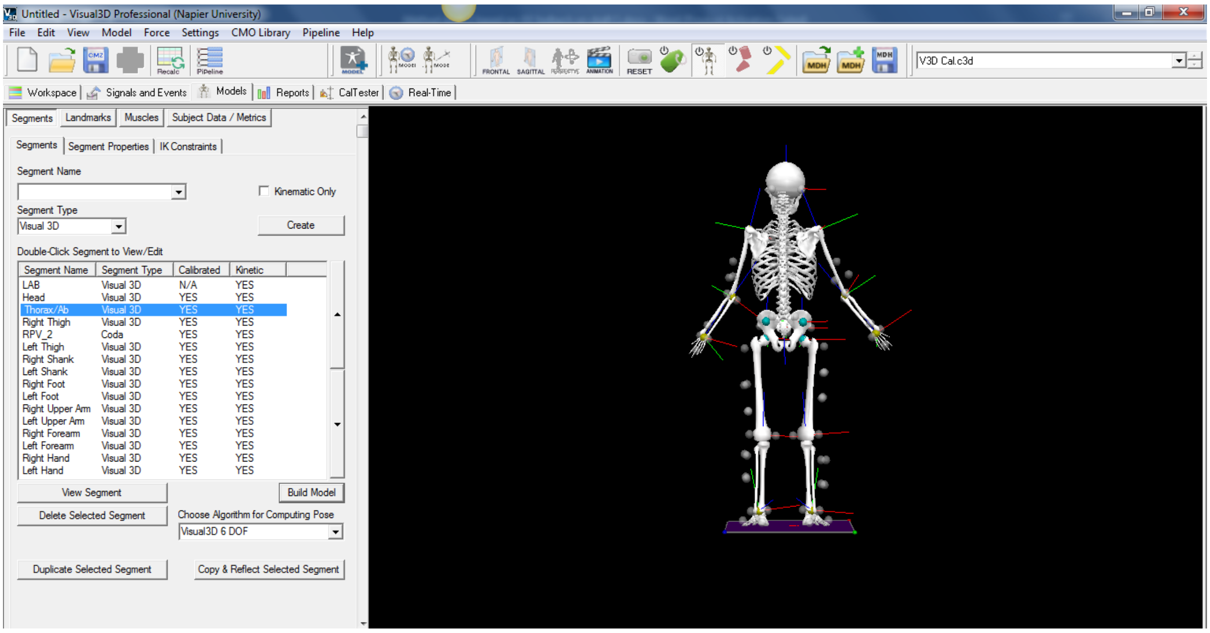
Segment Type: Visual 3D

Double-Click Segment to View/Edit

Segment Name	Segment Type	Calibrated	Kinetic
LAB	Visual 3D	N/A	YES
Head	Visual 3D	YES	YES
Thorax/Ab	Visual 3D	YES	YES
Right Thigh	Visual 3D	YES	YES
RPV_2	Coda	YES	YES
Left Thigh	Visual 3D	YES	YES
Right Shank	Visual 3D	YES	YES
Left Shank	Visual 3D	YES	YES
Right Foot	Visual 3D	YES	YES
Left Foot	Visual 3D	YES	YES
Right Upper Arm	Visual 3D	YES	YES
Left Upper Arm	Visual 3D	YES	YES
Right Forearm	Visual 3D	YES	YES
Left Forearm	Visual 3D	YES	YES
Right Hand	Visual 3D	YES	YES
Left Hand	Visual 3D	YES	YES

Choose Algorithm for Computing Pose: Visual3D 6 DOF

View of Markers in Visual 3D – Posterior View



V3D Cal.c3d

Segment Name:

Segment Type: Visual 3D

Double-Click Segment to View/Edit

Segment Name	Segment Type	Calibrated	Kinetic
LAB	Visual 3D	N/A	YES
Head	Visual 3D	YES	YES
Thorax/Ab	Visual 3D	YES	YES
Right Thigh	Visual 3D	YES	YES
RPV_2	Coda	YES	YES
Left Thigh	Visual 3D	YES	YES
Right Shank	Visual 3D	YES	YES
Left Shank	Visual 3D	YES	YES
Right Foot	Visual 3D	YES	YES
Left Foot	Visual 3D	YES	YES
Right Upper Arm	Visual 3D	YES	YES
Left Upper Arm	Visual 3D	YES	YES
Right Forearm	Visual 3D	YES	YES
Left Forearm	Visual 3D	YES	YES
Right Hand	Visual 3D	YES	YES
Left Hand	Visual 3D	YES	YES

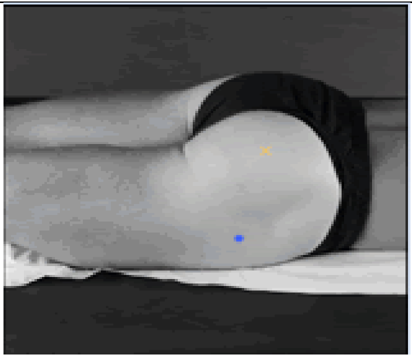
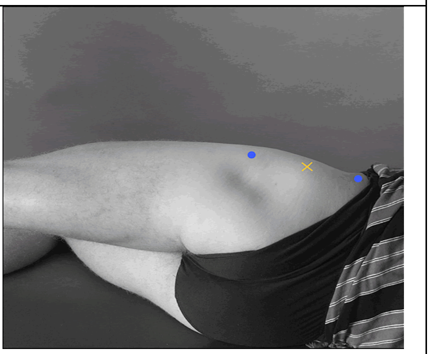
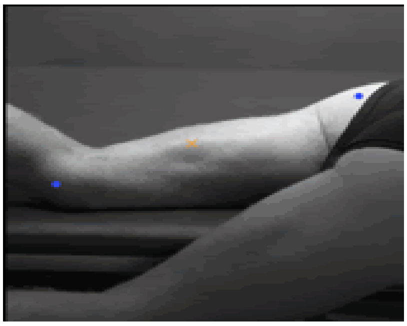
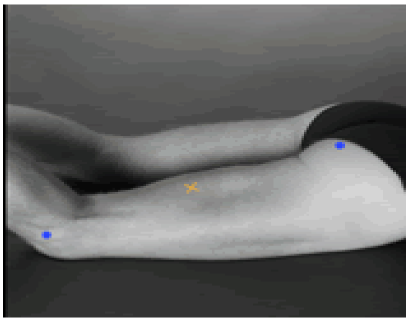
Choose Algorithm for Computing Pose: Visual3D 6 DOF

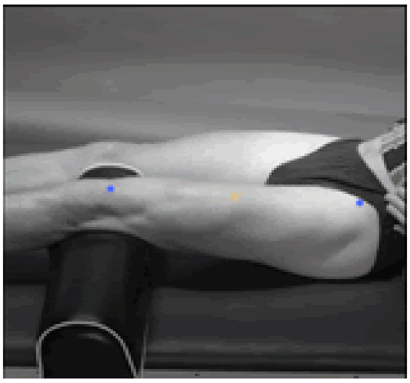
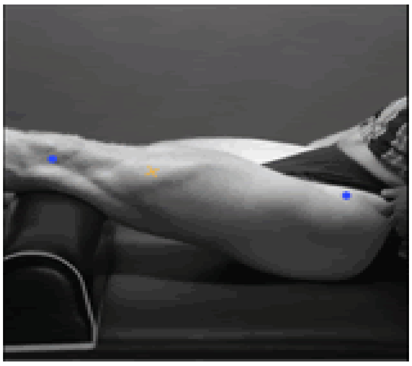
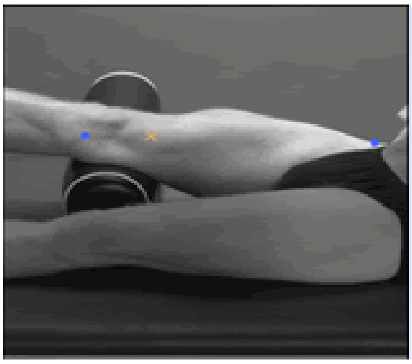
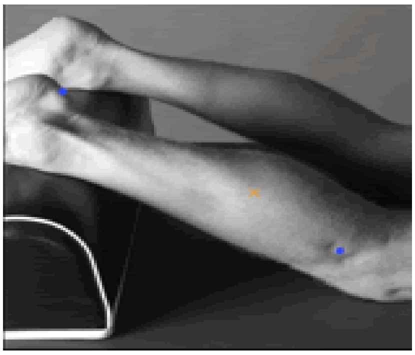
Appendix 5.6 Marker Set Table

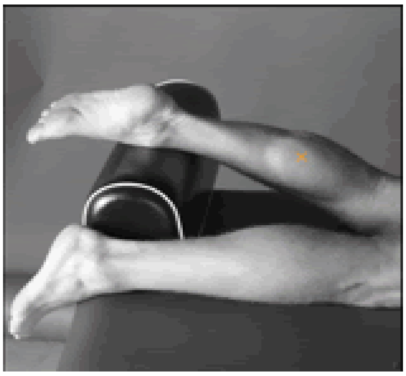
Marker set description

Body segment	**Description**	**Number of markers**
Head	Head band with markers	4
Trunk	A cluster placed on the upper back. Acromion and posterior superior iliac spine	8
Arms (upper) (on each side)	Acromion, upper arm cluster, medial and lateral epicondyles on each side	6
Arms (lower and hand) (on each side)	Medial and lateral epicondyles, styloid process of radius and ulna and lower portion of lower arm. 3rd metacarpal on each side	6
Pelvis	Anterior superior iliac spine, posterior iliac spine, sacrum.	5
Thigh (on each side)	Greater trochanter, upper leg cluster and mid-way between femoral lateral epicondyle and lateral epicondyle of tibia and femoral medial epicondyle and medial tibial epicondyle	7
Shank (on each side)	Mid-way between femoral lateral epicondyle and lateral epicondyle of tibia and femoral medial epicondyle and medial tibial epicondyle. A shank cluster. Lateral and medial malleolus	8
Ankle/foot (on each side)	Lateral and medial malleolus, calcaneus, head of metatarsal (1 and 5)	5

Appendix 5.7 SEMIAN Guideline EMG Placement

Muscle	**Measure from**	**Measure to**	**How far along (%)**	**Image**
Gluteus Maximus	Sacral vertebrae	Greater trochanter	50	
Gluteus Medias	Crista iliaca	Trochanter	50	
Semitendinosus	Ischial tuberosity	Medial epicondyle of the tibia	50	Flex knee to less than 90° 
Biceps Femoris	Ischial tuberosity	Lateral epicondyle of the tibia	50	Flex knee to less than 90° 

Rectus Femoris	Anterior spina iliac	Superior part of the patella	50	Use roller to elevate knee 
Vastus Lateralis	Anterior spina iliac	Superior part of the lateral side of patella	66	Use roller to elevate knee 
Vastus Medialis	Anterior Spina iliac	Anterior border of the medial ligament	80	Use roller to elevate knee 
Gastrocnemius Lateralis	Head of Fibula	The heel	33.3	Roller under ankle to flex knee 

Gastrocnemius medias	On the most bulbus part of the	-	-	Use roller to flex knee 

Appendix 5.8 Post Warm Up Physical Activity and Injury Form

Player hockey playing and training record

Week	**Hockey training and matches (circle as appropriate)**	**Strength and Conditioning (please specify)**	**Other activity (list any other physical activity)**	**Notes (Please list any other details e.g. injury)**
1	Monday training Tuesday training Wednesday game Saturday game Sunday game			
2	Monday training Tuesday training Wednesday game Saturday game Sunday game			
3	Monday training Tuesday training Wednesday game Saturday game Sunday game			
4	Monday training Tuesday training Wednesday game Saturday game Sunday game			
5	Monday training Tuesday training Wednesday game Saturday game Sunday game			
6	Monday training Tuesday training Wednesday game Saturday game Sunday game			
7	Monday training Tuesday training Wednesday game Saturday game Sunday game			
8	Monday training Tuesday training Wednesday game Saturday game Sunday game			

Appendix 5.9 Script for the Instructions for Each Task in Study 3 Testing

The sagittal plane hop

"Your first activity is a single leg hop in the sagittal plane – straight forwards and backwards. Start by standing on your right/left foot [dominant] foot behind the line facing towards force plate, hop over the hurdle and land on the force plate. When you hear the next beat from the metronome, hop backwards, over hurdle and land where you started, i.e. behind the line. The land and take off must in the same action i.e. land, bend knee and then extend leg with a push back. When you return to the starting position, return to an upright position as soon as possible. Your other foot is not allowed to touch the ground at any point until the trial is over. After each trial is over, I will let you know if it successful".

These instructions are followed by a demonstration. The participant has 3 sub-max practice attempts.

The hop and twist

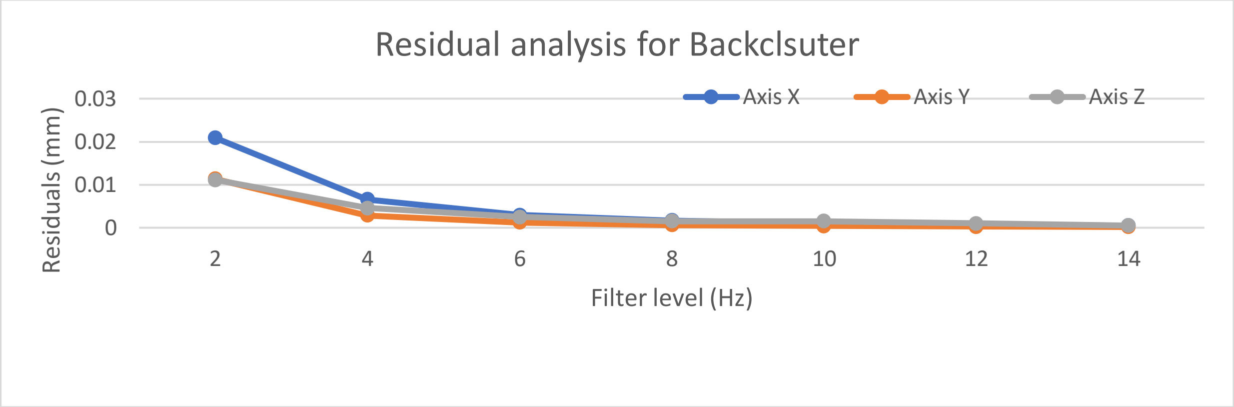
"Your second activity is a single leg hop with twist. Start by standing next to the force plate. When I say go step onto the force plate [point to the force plate area] and stand with right/leg [dominant] foot on the force platform, with their non-dominant foot off the ground, and get balanced. When you are ready hop as high as you can and turn 180°, twist towards your non-dominant shoulder (anticlockwise), landing on the same foot and on the force plate. After landing return to upright as soon as possible and pause there. When you land, keep your non-dominant foot off the ground until the trial is over, I will let you know."
[These instructions will be followed by a demonstration and 3 sub-max practice attempts].

The unanticipated cut

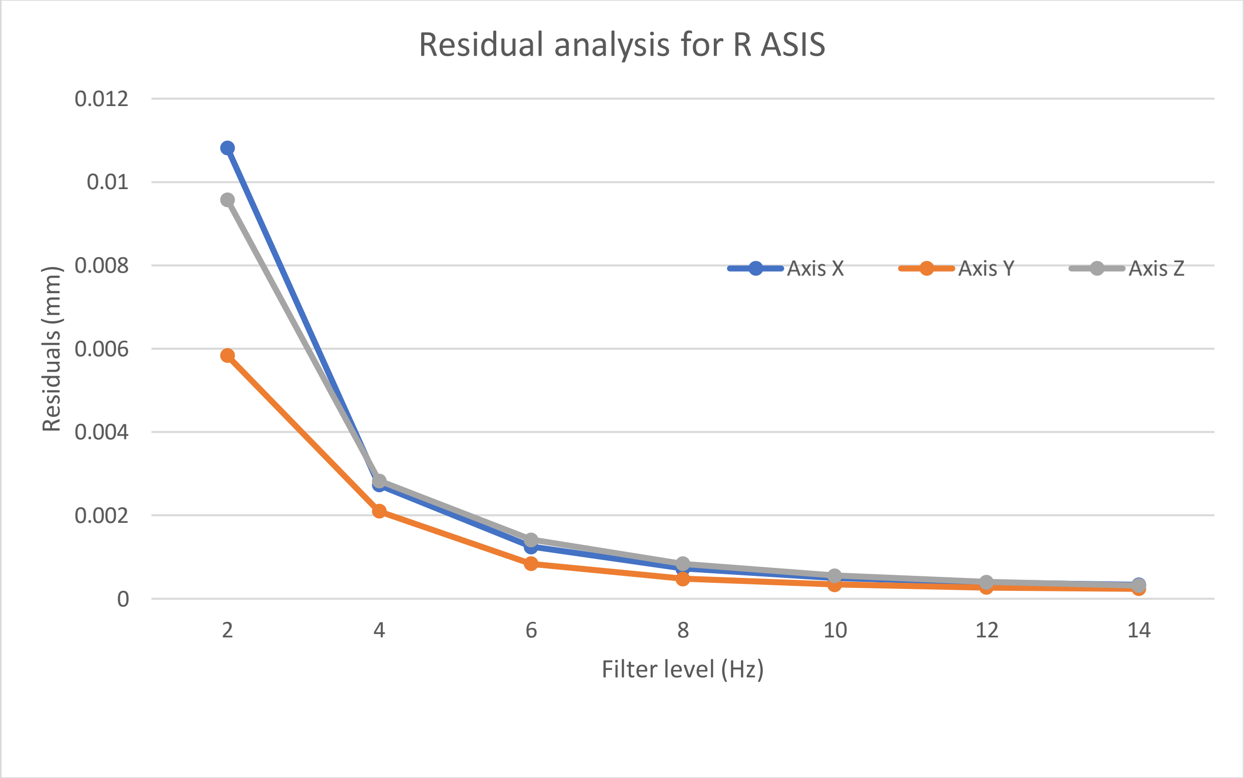
"Your third activity is an unanticipated cut. Approach the force plate with a 2-step run up going through the timing gates, land with one foot on each force plates [show them the force plates to land on], as you go through the timing gates, a green light will appear/flash on one of the two gates in front of you– the system will randomly select which side you have to go. As soon as you land, sidestep cut at a 45° angle to that side as quickly as possible, running towards the gate. You must land and flex knees and then push off from that position towards the flashing light. You must push off with the opposite foot to the direction you are going to run to – so if the left light flashes push off from your right leg. Run to the gate as quickly as you can, run through the gate and before slowing down.”

These instructions are followed by a demonstration. The participant has 3 sub-max practice attempts.

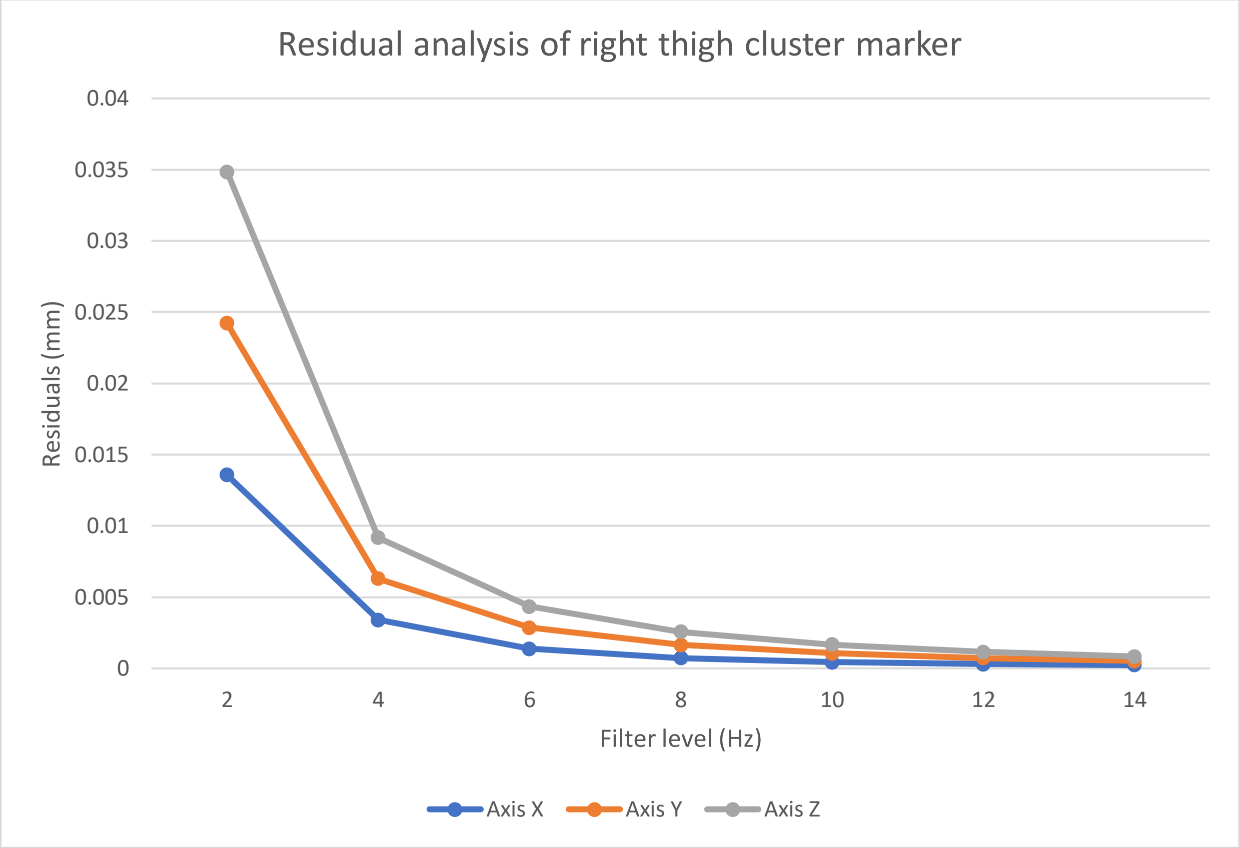
Appendix 5.10 Residual Analysis



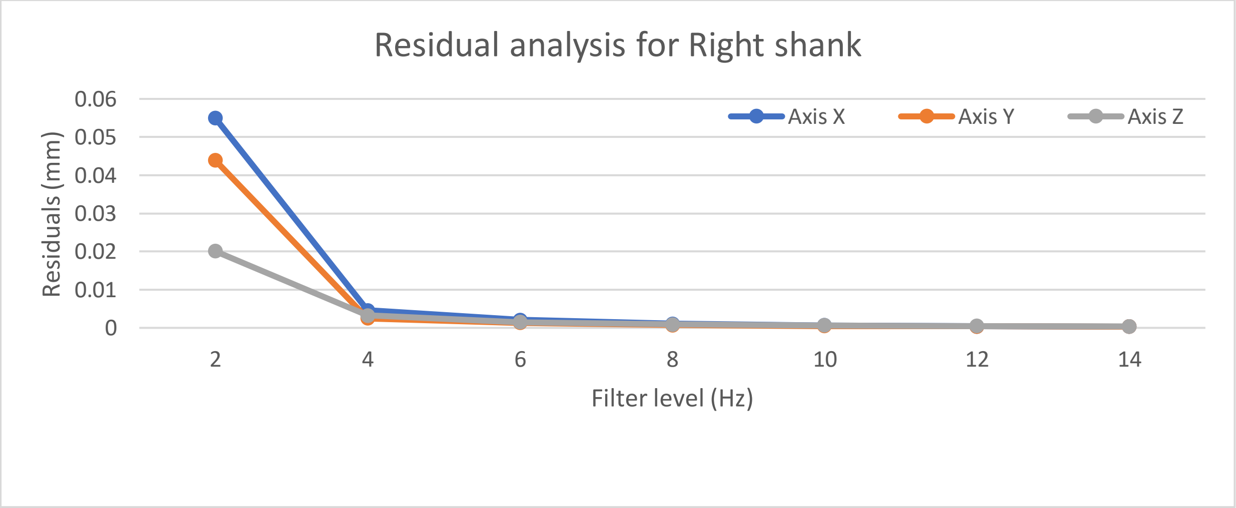
Residual analysis of a back-cluster marker



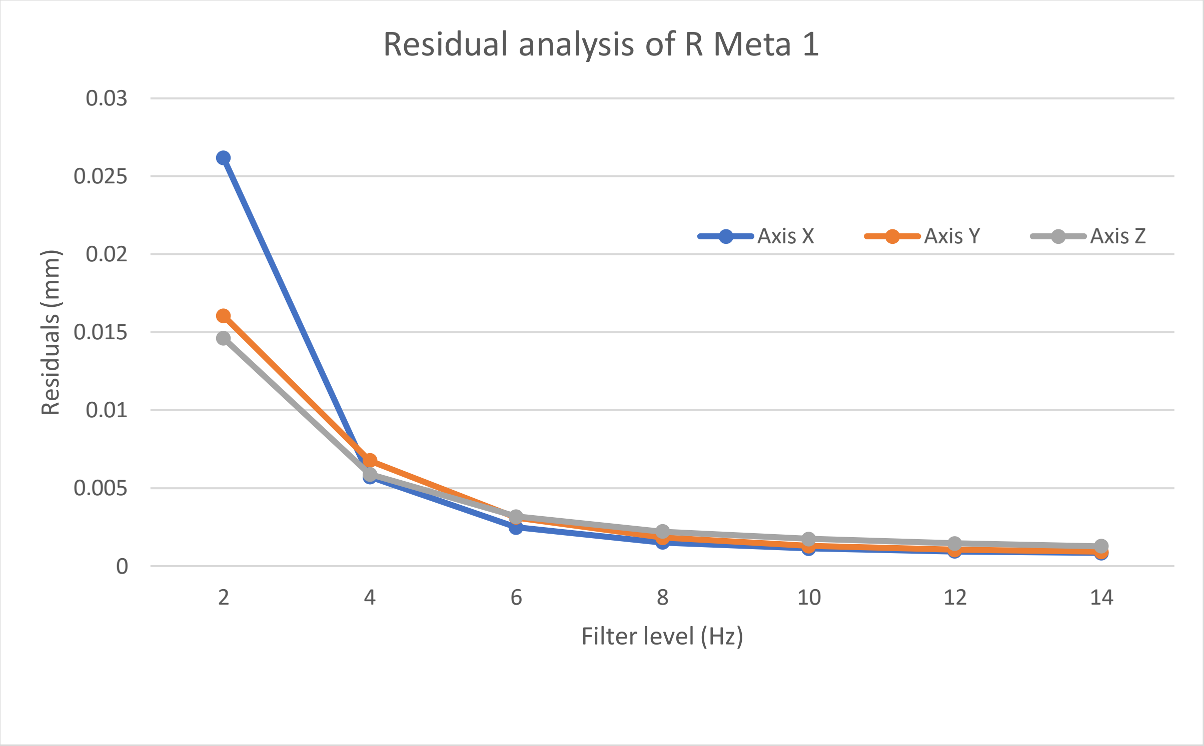
Residual analysis of right ASIS marker



Residual analysis of a right thigh cluster marker



Residual analysis of a right shank marker



Residual analysis of the right metatarsal marker

Appendix 5.11 Axis Interpretation

Axis interpretation

		Axis	
Body segment	**X**	**Y**	**Z**
Trunk	Negative = Flexion Positive = extension	Negative = Lateral flexion to the right Positive = lateral flexion to the left	Positive = rotation to the left Negative = rotation to the right
Hip (right leg)	Negative = Flexion Positive = extension	Negative = abduction Positive = adduction	Positive = rotation to the left Negative = rotation to the right
Knee (right leg)	Negative = Flexion Positive = extension	Negative = abduction Positive = adduction	Positive = rotation to the left Negative = rotation to the right
Ankle (right leg)	Negative = Flexion Positive = extension	Negative = abduction Positive = adduction	Positive = rotation to the left Negative = rotation to the right
Hip (left leg)	Negative = Flexion Positive = extension	Positive = abduction Negative = adduction	Positive = rotation to the right Negative = rotation to the left
Knee (left leg)	Negative = Flexion Positive = extension	Negative = adduction Positive = abduction	Positive = rotation to the left Negative = rotation to the right
Ankle (left leg)	Dorsi Flexion = negative Plantar flexion = positive	Negative = adduction Positive = abduction	Positive = rotation to the right Negative = rotation to the left

Appendix 5.12 Participant Information

Control group

Participant number	**Height (cm)**	**Weight (kg) (Before)**	**Weight (kg) (After)**	**Diff (kg)**	**Number of games**	**Number training sessions**	**Number of training sessions (not hockey)**	**Experience (yrs)**	**Number of injuries during intervention**	**Information on injury**
1	159	68	66.2	-1.8	1	1	2	7	0	
2	158	60	59.8	-0.2	1	2	1.5	9	0	
3	172.2	66	65.3	-0.7	2	1	1	11	0	
4	169.5	67.3	67.3	0	3	1	1	13	0	
5	157	55.3	57.6	-2.3	2	2	2	14	0	
6	163	64	63.5	-0.5	1	1	1	10	1	Overuse - training - No timeloss
7	171.5	61.3	61.3	0	1	1	1	5	0	
8	165	56	55.5	-0.5	2	1	1	8	0	
9	166.5	59.3	58	-1.3	2	1	1	6	0	
10	166	63	64.5	1.5	2	2	0	8	1	Noncontact - hamstring strain missed 1 week
11	1740	70.5	73	-2.5	1	1	1	10	0	
12	161	55	54.1	-0.9	1	1	1	5	0	
13	168	86	84	-2	1	1	1	10	0	
14	170	65	65.3	-0.3	1	1	0	10	0	
15	168	67.6	70	2.4	2	1	1	12	0	
16	160	52	52	0	1	1	1	5	0	
17	165	52	51.5	-0.5	2	1	0	7	0	
18	167	61.5	59.8	-1.7	2	2	1	10	1	Non-contact hamstring strain 1 day timeloss

Intervention group

Participant number	Height (cm)	Weight (kg) (Before)	Weight (kg) (After)	Diff (kg)	Number of games	Number training sessions*	Number of training sessions (not hockey)	Experience (yrs)	Number of injuries during intervention	Information on injury
1	162	63	63	0	2	1	2	16	0	
2	166	58	25.1	0.1	2	1	1	10	0	
3	168	65.8	68.2	2.4	1	1	2	11	1	Recurrent injury - ankle - warm up - restricted activities
4	170	74	74	0	2	1	2	14	0	
5	170	70.5	73	2.5	1	1	1	10	0	
6	161	58	57	-1	2	1	1	12	0	
7	173	71	71	0	2	1	0.5	12	0	
8	173.5	76	75.6	-0.4	2	1	0	9	0	
9	169	77.5	77	-0.5	0.75	0	0	10	0	
10	159	61.5	61	-0.5	2	1	0.5	13	1	Contact knee injury
11	165	61	61	0	2	1	0	9	0	
12	173	67.2	67.1	3.4	2	1	1	14	0	
13	179	67.2	67.1	-0.1	2	1	2	7	0	
14	173	66	66	0	2	1	1	10	0	
15	163	77	77	0	2	1	2	9	0	
16	165	61.2	61	-0.2	2	1	0	11	0	
17	166	62.2	61.5	-0.7	2	1	2	15	0	
18	160	66.2	67.2	1	2	1	2	10	0	
19	173	60	61.5	1.5	2	1	0.5	9	0	
20	163	61	61.1	0.1	2	1	1	13		

*not intervention or hockey sessions

Appendix 5.13 Study 3 Statistical Information

Sagittal plane hop - EMG

Variable	**Descriptives**	**Statistic**	**df**	**F value**	**P Significance**	**Effect size**
GasMed 100	CON Pre 30.17 (16.1) CON Post 36.42(17.2) INT Pre 34.94 (17.8) INT Post 45.68 (14.7)	main Time*Group Between	1, 36 1, 36 1, 36	13.549 0.946 2.114	0.001 0.337 0.155	0.272 0.026 0.055
GasMed 30	CON Pre 22.34 (10.1) CON Post 26.33 (13.6) INT Pre 24.86 (13.6) INT Post 33.77 (11.7)	main Time*Group Between	1, 36 1, 36 1, 36	10.978 1.610 2.01	0.002 0.213 0.165	0.234 0.043 0.053
GasMed 50	CON Pre 22.52 (11.8) CON Post 25.3 (14.0) INT Pre 24.61 (13.7) INT Post 26.15 (11.0)	main Time*Group Between	1, 36 1, 36 1, 36	2.344 0.613 0.517	0.135 0.439 0.477	0.061 0.017 0.014
GasMed IC to MKF	CON Pre 37.57 (7.8) CON Post 41.89 (9.7) INT Pre 41.3 (12.0) INT Post 47.72 (3.6)	main Time*Group Between	1, 36 1, 36 1, 36	12.248 0.468 3.912	0.001 0.498 0.056	0.254 0.013 0.098
GasMed Time to peak	CON Pre -0.1040 (0.02) CON Post -0.1103 (0.03) INT Pre -0.1004 (0.02) INT Post -0.1172 (0.02)	main Time*Group Between	1, 36 1, 36 1, 36	4.885 1.021 0.055	0.034 0.319 0.816	0.119 0.028 0.002
GasLat 100	CON Pre 25.56 (11.7) CON Post 31.17 (16.1) INT Pre 33.55 (19.8) INT Post 42.18 (14.6)	main Time*Group Between	1, 36 1, 36 1, 36	16.63 0.746 3.808	0.000 0.394 0.059	0.316 0.02 0.096
GasLat 30	CON Pre 20.86 (10.0) CON Post 26.1 (13.5) INT Pre 27.33 (17.4) INT Post 28.84 (10.4)	main Time*Group Between	1, 36 1, 36 1, 36	2.662 0.811 1.499	0.111 0.374 0.229	0.069 0.022 0.04
GasLat 50	CON Pre 19.69 (7.3) CON Post 23.33 (12.6) INT Pre 24.82 (12.2) INT Post 25.47 (9.0)	main Time*Group Between	1, 36 1, 36 1, 36	1.323 0.641 1.610	0.258 0.429 0.213	0.035 0.017 0.043
GasLat IC to MKF	CON Pre 37.65 (6.0) CON Post 42.42 (9.4) INT Pre 41.83 (11.3) INT Post 49.02 (7.6)	main Time*Group Between	1, 36 1, 36 1, 36	13.629 0.551 5.132	0.001 0.463 0.03	0.275 0.015 0.125
GasLat Time to peak	CON Pre -0.1178 (0.02) CON Post -0.1094 (0.03) INT Pre -0.1186 (0.02) INT Post -0.112 (0.02)	main Time*Group Between	1, 36 1, 36 1, 36	2.132 0.03 0.07	0.153 0.863 0.793	0.056 0.001 0.002
HamMed 100	CON Pre 44.64 (14.4) CON Post 44.29 (22.0) INT Pre 46.2 (16.8) INT Post 47.04 (12.7)	main Time*Group Between	1, 36 1, 36 1, 36	0.009 0.053 0.201	0.924 0.819 0.656	0.000 0.001 0.006
HamMed 30	CON Pre 37.12 (14.0) CON Post 33.93 (19.4) INT Pre 43.27 (17.3) INT Post 37.45 (13.2)	main Time*Group Between	1, 36 1, 36 1, 36	1.476 0.126 1.687	0.232 0.725 0.202	0.039 0.003 0.045
HamMed 50	CON Pre 37.53 (14.6) CON Post 40.33 (13.3) INT Pre 41.2 (12.9) INT Post 40.72 (11.7)	main Time*Group Between	1, 36 1, 36 1, 36	0.248 0.495 0.324	0.621 0.486 0.573	0.007 0.014 0.009
HamMed IC to MKF	CON Pre 54.78 (8.2) CON Post 54.26 (6.4) INT Pre 55.66 (6.1) INT Post 54.93 (7.2)	main Time*Group Between	1, 36 1, 36 1, 36	0.153 0.004 0.228	0.698 0.948 0.636	0.004 0.000 0.006
HamMed Time to peak	CON Pre -0.1314 (0.3) CON Post -0.1246 (0.02) INT Pre -0.1343 (0.04) INT Post -0.1282 (0.4)	main Time*Group Between	1, 36 1, 36 1, 36	1.702 0.005 0.091	0.200 0.946 0.765	0.045 0.000 0.003
HamLat 100	CON Pre 41.86 (15.6) CON Post 46.7 (21.1) INT Pre 45.66 (18.7) INT Post 46.71 (10.8)	main Time*Group Between	1, 36 1, 36 1, 36	1.437 0.595 0.150	0.239 0.445 0.701	0.38 0.016 0.004
HamLat 30	CON Pre 33.01 (12.2) CON Post 39.61 (22.0) INT Pre 40.93 (20.9)	main Time*Group Between	1, 36 1, 36 1, 36	0.435 1.371 0.700	0.514 0.249 0.408	0.012 0.037 0.019

	INT Post 39.08 (12.7)					
HamLat 50	CON Pre 32.77 (11.4) CON Post 37.4 (14.5) INT Pre 35.8 (10.8) INT Post 37.33 (10.2)	main Time*Group Between	1, 36 1, 36 1, 36	2.158 0.548 0.215	0.151 0.464 0.646	0.057 0.015 0.006
HamLat IC to MKF	CON Pre 56.14 (10.3) CON Post 58.54 (5.9) INT Pre 54.38 (7.6) INT Post 59.41 (4.8)	main Time*Group Between	1, 36 1, 36 1, 36	5.943 0.750 0.059	0.02 0.392 0.810	0.142 0.02 0.002
HamLat Time to peak	CON Pre -0.1431 (0.02) CON Post -0.1346 (0.04) INT Pre -0.1308 (0.04) INT Post -0.1327 (0.03)	main Time*Group Between	1, 36 1, 36 1, 36	0.291 0.740 0.688	0.593 0.395 0.412	0.008 0.02 0.019
VM 100	CON Pre 67.54 (19.1) CON Post 63.5 (19.5) INT Pre 66.91 (19.4) INT Post 73.89 (12.1)	main Time*Group Between	1, 36 1, 36 1, 36	0.253 3.494 0.977	0.618 0.07 0.33	0.007 0.088 0.026
VM 30	CON Pre 48.56 (21.7) CON Post 45.40 (23.0) INT Pre 50.40 (20.5) INT Post 55.34 (17.1)	main Time*Group Between	1, 36 1, 36 1, 36	0.072 1.5 1.026	0.790 0.229 0.318	0.002 0.04 0.028
VM 50	CON Pre 45.09 (17.4) CON Post 40.11 (13.6) INT Pre 44.64 (13.4) INT Post 47.4 (13.3)	main Time*Group Between	1, 36 1, 36 1, 36	0.288 3.565 0.655	0.595 0.067 0.424	0.008 0.09 0.018
VM IC to MKF	CON Pre 56.14 (10.3) CON Post 49.99 (9.5) INT Pre 50.02 (7.8) INT Post 51.35 (9.2)	main Time*Group Between	1, 36 1, 36 1, 36	2.360 5.676 0.894	0.133 0.023 0.351	0.062 0.136 0.024
VM Time to peak	CON Pre -0.0247 (0.07) CON Post -0.034 (0.07) INT Pre -0.0367 (0.07) INT Post -0.0312 (0.05)	main Time*Group Between	1, 36 1, 36 1, 36	0.024 0.344 0.067	0.877 0.561 0.797	0.001 0.009 0.002
VL 100	CON Pre 54.33 (18.1) CON Post 52.53 (18) INT Pre 51.98 (16.5) INT Post 60.84 (13.4)	main Time*Group Between	1, 36 1, 36 1, 36	1.858 4.237 0.401	0.181 0.047 0.531	0.049 0.105 0.011
VL 30	CON Pre 42.75 (16.2) CON Post 41.12 (18.5) INT Pre 42.97 (20.9) INT Post 44.76 (14.9)	main Time*Group Between	1, 36 1, 36 1, 36	0.001 0.397 0.397	0.976 0.533 0.533	0.000 0.011 0.011
VL 50	CON Pre 39.07 (13.4) CON Post 34.67 (12.8) INT Pre 42.37 (14.8) INT Post 43.01 (17.6)	main Time*Group Between	1, 36 1, 36 1, 36	0.474 0.856 2.135	0.496 0.361 0.153	0.013 0.023 0.056
VL IC to MKF	CON Pre 47.22 (7.4) CON Post 45.36 (7.6) INT Pre 47.48 (9.5) INT Post 48.78 (7.3)	main Time*Group Between	1, 36 1, 36 1, 36	0.012 0.819 0.739	0.913 0.371 0.396	0.000 0.022 0.02
VL Time to peak	CON Pre -0.0657 (0.06) CON Post -0.796 (0.06) INT Pre -0.0602 (0.07) INT Post -0.0492 (0.05)	main Time*Group Between	1, 36 1, 36 1, 36	0.016 1.094 1.067	0.901 0.303 0.309	0.000 0.029 0.029
RF 100	CON Pre 55.19 (16.6) CON Post 48.6 (16.5) INT Pre 47.82 (15.3) INT Post 54.6 (12.7)	main Time*Group Between	1, 36 1, 36 1, 36	0.003 9.113 0.023	0.958 0.005 0.881	0.000 0.202 0.001
RF 30	CON Pre 41.5 (16.5) CON Post 40.17 (15.4) INT Pre 41.3 (16.3) INT Post 38.84 (14.8)	main Time*Group Between	1, 36 1, 36 1, 36	0.537 0.047 0.031	0.469 0.829 0.862	0.015 0.001 0.001
RF 50	CON Pre 38.88 (12.9) CON Post 35.52 (12.2) INT Pre 43.16 (14.0) INT Post 42.56 (16.4)	main Time*Group Between	1, 36 1, 36 1, 36	0.531 0.258 2.389	0.471 0.614 0.131	0.015 0.007 0.062
RF IC to MKF	CON Pre 44.51 (7.7) CON Post 44.32 (8.2) INT Pre 44.33 (9.6) INT Post 46.74 (9.1)	main Time*Group Between	1, 36 1, 36 1, 36	0.871 1.184 0.677	0.357 0.284 0.677	0.024 0.032 0.005
RF Time to peak	CON Pre -0.0585 (0.06) CON Post -0.0864 (0.05)	main Time*Group	1, 36 1, 36	0.278 4.148	0.601 0.049	0.008 0.103

	INT Pre -0.072 (0.06) INT Post -0.0556 (0.06)	Between	1, 36	0.370	0.547	0.01
GMed 100	CON Pre 26.52 (9.8) CON Post 29.72 (11.9) INT Pre 32.71 (9.9) INT Post 35.54 (13.2)	main Time*Group Between	1, 36 1, 36 1, 36	1.590 0.006 4.628	0.215 0.939 0.038	0.042 0.000 0.114
GMed 30	CON Pre 22.35 (10.1) CON Post 28.95 (10.8) INT Pre 24.86 (13.6) INT Post 33.1 (9.0)	main Time*Group Between	1, 36 1, 36 1, 36	9.421 0.116 1.592	0.004 0.735 0.215	0.207 0.003 0.042
GMed 50	CON Pre 39.55 (12.4) CON Post 33.84 (8.5) INT Pre 37.42 (11.5) INT Post 38.67 (14.1)	main Time*Group Between	1, 36 1, 36 1, 36	1.310 3.206 0.164	0.260 0.082 0.688	0.035 0.082 0.005
GMed IC to MKF	CON Pre 34.67 (5.7) CON Post 38.2 (8.0) INT Pre 36.86 (7.9) INT Post 43.89 (8.9)	main Time*Group Between	1, 36 1, 36 1, 36	12.085 1.316 3.862	0.001 0.259 0.057	0.251 0.035 0.097
GMed Time to peak	CON Pre -0.1228 (0.03) CON Post -0.1179 (0.03) INT Pre -0.1143 (0.03) INT Post -0.1269 (0.03)	main Time*Group Between	1, 36 1, 36 1, 36	0.374 1.869 0.001	0.545 0.18 0.974	0.01 0.049 0.000
GMax 100	CON Pre 36.19 (11.1) CON Post 34.09 (10.1) INT Pre 34.53 (9.0) INT Post 37.5 (11.6)	main Time*Group Between	1, 36 1, 36 1, 36	0.061 2.019 0.09	0.807 0.164 0.766	0.002 0.053 0.002
GMax 30	CON Pre 33.67 (12.7) CON Post 33.6 (12.7) INT Pre 33.89 (9.5) INT Post 33.92 (14.9)	main Time*Group Between	1, 36 1, 36 1, 36	0.000 0.001 0.006	0.994 0.980 0.937	0.000 0.000 0.000
GMax 50	CON Pre 28.75 (8.2) CON Post 25.02 (7.1) INT Pre 25.72 (8.2) INT Post 32.17 (8.7)	main Time*Group Between	1, 36 1, 36 1, 36	0.589 8.229 1.115	0.448 0.007 0.298	0.016 0.186 0.03
GMax IC to MKF	CON Pre 37.4 (6.4) CON Post 39.96 (8.6) INT Pre 39.14 (6.9) INT Post 43.62 (11.3)	Main Time*Group Between	1, 36 1, 36 1, 36	4.930 0.367 1.391	0.033 0.549 0.249	0.120 0.01 0.037
GMax Time to peak	CON Pre -0.1292 (0.04) CON Post -0.1163 (0.02) INT Pre -0.1204 (0.02) INT Post -0.1093 (0.02)	Main Time*Group Between	1, 36 1, 36 1, 36	4.687 0.028 1.669	0.037 0.869 0.205	0.115 0.001 0.044

Sagittal plane hop - Kinematics and Kinetics

Variable	Descriptives	Statistic	df	F value	Sig	Effect size
Trunk – Flexion	CON Pre 171.9 (6.4) CON Post 173.45 (6.7) INT Pre 173.84 (3.6) INT Post 173.26 (5.5)	main Time*Group Between	1, 36 1, 36 1, 36	0.359 1.636 0.436	0.553 0.209 0.513	0.01 0.043 0.012
Trunk – Lat Flexion	CON Pre -0.75 (3.3) CON Post -0.72 (4.7) INT Pre -1.70 (4.8) INT Post 0.87 (4.1)	main Time*Group Between	1, 36 1, 36 1, 36	3.55 3.391 0.072	0.068 0.074 0.790	0.09 0.086 0.02
Trunk Rotation	CON Pre 2.65 (4.8) CON Post 2.3 (5.5) INT Pre 3.16 (3.6) INT Post 3.06 (4.0)	main Time*Group Between	1, 36 1, 36 1, 36	0.113 0.039 0.252	0.739 0.845 0.619	0.003 0.001 0.007
Max Lat Flexion	CON Pre -13.36 (6.8) CON Post -13.16 (6.6) INT Pre -13.17 (5.5) INT Post -10.32 94.2)	main Time*Group Between	1, 36 1, 36 1, 36	2.434 33.034 0.880	0.186 0.186 0.354	0.048 0.048 0.024
Lat C of G	CON Pre 0.041 (0.007) CON Post 0.003 (0.008) INT Pre 0.0093 (0.008) INT Post 0.006 (0.009)	Main Time*Group Between	1, 36 1, 36 1, 36	1.797 0.440 3.67	0.189 0.511 0.063	0.048 0.012 0.093
Hip – Flexion	CON Pre 34.39 (6.8) CON Post 33.28 (8.1) INT Pre 32.76 (8.7) INT Post 28.47 (8.2)	main Time*Group Between	1, 36 1, 36 1, 36	7.4 51.295 1.742	0.01 0.1 0.195	0.171 0.073 0.046
Hip – frontal plane motion	CON Pre -5.18 (4.2) CON Post -5.36 (5.0) INT Pre -6.39 (4.4) INT Post -5.41 (4.5)	main Time*Group Between	1, 36 1, 36 1, 36	4.55 .935 0.221	0.504 0.34 0.641	0.012 0.025 0.006
Hip – axial rotation	CON Pre 8.43 (9.5) CON Post 3.50 (5.6) INT Pre 4.86 (6.5) INT Post 3.88 (8.0)	main Time*Group Between	1, 36 1, 36 1, 36	4.992 2.224 0.594	0.032 0.145 0.446	0.122 0.058 0.016
Knee – Flexion	CON Pre -15.68 (4.5) CON Post -15.6 (5.4) INT Pre -13.37 (5.7) INT Post -13.01 (5.0)	main Time*Group Between	1, 36 1, 36 1, 36	0.063 0.025 2.923	0.803 0.875 0.096	0.002 0.001 0.075
Knee – ab/adduction	CON Pre 1.34 (4.8) CON Post 0.044 (4.2) INT Pre 0.80 (2.8) INT Post 0.57 (2.9)	main Time*Group Between	1, 36 1, 36 1, 36	0.552 2.102 0.035	0.216 0.462 0.853	0.042 0.015 0.001
Knee - Rotation	CON Pre -9.27 (6.9) CON Post -6.55 (5.9) INT Pre -5.11 (7.4) INT Post -6.50 (6.8)	main Time*Group Between	1, 36 1, 36 1, 36	0.919 8.643 1.00	0.344 0.006 0.324	0.025 0.194 0.027
Max Knee Add	CON Pre -0.8 (2.0) CON Post 1.29 (1.0) INT Pre 0.51 (1.7) INT Post -0.42 (1.2)	main Time*Group Between	1, 36 1, 36 1, 36	4.365 29.242 0.232	0.044 0.000 0.633	0.108 0.448 0.006
Max Knee Abd	CON Pre 9.61 (3.6) CON Post 7.4 (3.1) INT Pre 7.81 (3.3) INT Post 6.89 (2.0)	main Time*Group Between	1, 36 1, 36 1, 36	7.001 1.200 2.058	0.012 0.281 0.160	0.163 0.032 0.054
Knee Excursion	CON Pre 8.83 (2.5) CON Post 8.54 (3.0) INT Pre 8.35 (2.4) INT Post 6.32 (1.8)	main Time*Group Between	1, 36 1, 36 1, 36	5.989 3.413 4.620	0.019 0.073 0.038	0.143 0.087 0.114
Ankle – Flexion	CON Pre 39.67 (4.7) CON Post 41.9 (5.4) INT Pre 41.93 (3.7) INT Post 41.93 (5.3)	main Time*Group Between	1, 36 1, 36 1, 36	2.098 2.091 0.699	0.156 0.157 0.409	0.055 0.055 0.019
Ankle – frontal plane motion	CON Pre -4.81 (4.6) CON Post -3.67 (6.0) INT Pre -8.6 (5.6) INT Post -7.05 (5.0)	main Time*Group Between	1, 36 1, 36 1, 36	3.482 0.821 5.185	0.07 0.085 0.029	0.088 0.002 0.126
Ankle – axial rotation	CON Pre -15.37 (8.7) CON Post -13.3 (6.6) INT Pre -15.41 (6.8) INT Post -15.95 (6.6)	main Time*Group Between	1, 36 1, 36 1, 36	0.440 0.1299 0.426	0.511 0.262 0.518	0.012 0.035 0.012

Peak vGRF	CON Pre 1181.3 (222.6) CON Post 1487 (203.1) INT Pre 1584.1 (178.1) INT Post 1562.7 (195)	main Time*Group Between	1, 36 1, 36 1, 36	0.105 0.314 2.203	0.748 0.579 0.146	0.003 0.009 0.058
Norm vGRF	CON Pre 2.45 (0.19) CON Post 2.44 (0.3) INT Pre 2.46 (0.2) INT Post 2.43 (0.3)	main Time*Group Between	1, 36 1, 36 1, 36	.211 0.02 0.000	0.648 0.89 0.998	0.006 0.001 0.000
RFD	CON Pre 14.25 (2.9) CON Post 14.6 (2.7) INT Pre 13.27 (1.5) INT Post 11.64 (2.3)	main Time*Group Between	1, 36 1, 36 1, 36	1.88 4.333 10.427	0.179 0.045 0.003	0.05 0.107 0.225
Trunk flexion MKF	CON Pre 163.16 (8.9) CON Post 164.22 (6.5) INT Pre 167.57 (7.1) INT Post 168.6 (8.7)	main Time*Group Between	1, 36 1, 36 1, 36	1.026 0.000 3.559	0.318 0.995 0.067	0.28 0.000 0.09
Trunk frontal plane motion MKF	CON Pre -11.98 (6.3) CON Post -11.82 (6.8) INT Pre -11.62 (5.5) INT Post -9.1 (5.8)	main Time*Group Between	1, 36 1, 36 1, 36	2.461 1.905 0.865	0.125 0.176 0.359	0.064 0.05 0.023
Trunk axial rotation MKF	CON Pre -2.46 (4.6) CON Post -2.4 (7.2) INT Pre -0.54 (5.2) INT Post 0.11 (4.9)	main Time*Group Between	1, 36 1, 36 1, 36	0.303 0.206 1.733	0.585 0.652 0.196	0.008 0.006 0.046
Hip flexion MKF	CON Pre 48.46 (7.4) CON Post 33.3 (8.1) INT Pre 45.69 (9.7) INT Post 28.47 (8.2)	main Time*Group Between	1, 36 1, 36 1, 36	7.896 3.556 3.688	0.008 0.067 0.063	0.18 0.09 0.093
Hip frontal plane motion MKF	CON Pre 6.8 (4.0) CON Post 7.36 (3.2) INT Pre 6.52 (3.6) INT Post 6.01 (4.2)	main Time*Group Between	1, 36 1, 36 1, 36	0.003 1.298 0.53	0.957 0.262 0.471	0.000 0.035 0.015
Hip axial rotation MKF	CON Pre 6.94 (8.7) CON Post 2.74 (5.0) INT Pre 4.51 (6.8) INT Post 3.64 (6.6)	main Time*Group Between	1, 36 1, 36 1, 36	3.559 1.533 0.181	0.067 0.224 0.673	0.09 0.041 0.005
Knee flexion MKF	CON Pre -58.3 (8.7) CON Post -59.1 (6.8) INT Pre -54.90 (7.5) INT Post -54.26 (6.6)	main Time*Group Between	1, 36 1, 36 1, 36	0.007 0.457 4.229	0.934 0.503 0.047	0.000 0.013 0.105
Knee frontal plane MKF	CON Pre 6.03 (6.4) CON Post 3.46 (5.9) INT Pre 3.27 (6.3) INT Post 3.59 (5.1)	main Time*Group Between	1, 36 1, 36 1, 36	1.417 2.311 0.610	0.242 0.137 0.440	0.038 0.06 0.017
Knee axial rotation MKF	CON Pre 4.16 (6.0) CON Post 5.12 (6.5) INT Pre 5.12 (6.5) INT Post 3.56 (5.4)	main Time*Group Between	1, 36 1, 36 1, 36	0.004 2.627 0.107	0.950 0.114 0.746	0.000 0.068 0.003
Ankle flexion MKF	CON Pre 87.52 (6.5) CON Post 88.19 (4.3) INT Pre 87.85 (5.0) INT Post 87.53 (4.7)	main Time*Group Between	1, 36 1, 36 1, 36	0.053 0.399 0.012	0.819 0.532 0.912	0.001 0.011 0.000
Ankle frontal plane motion MKF	CON Pre -21.83 (6.5) CON Post -20.14 (7.5) INT Pre -22.71 (9.5) INT Post -23.55 (6.2)	main Time*Group Between	1, 36 1, 36 1, 36	0.111 0.978 1.042	0.741 0.329 0.314	0.003 0.026 0.028
Ankle axial rotation MKF	CON Pre -3.27 (4.7) CON Post -1.72 (5.0) INT Pre -3.58 (4.9) INT Post -4.5 9 (5.4)	main Time*Group Between	1, 36 1, 36 1, 36	0.128 1.954 1.277	0.723 0.171 0.266	0.004 0.051 0.034

Study 3 Stats table – Hop and twist – EMG

Variable	Descriptives	Statistic	df	F value	P Significance	Effect size
GasMed 100	CON Pre 49.2 (15.9)	main	1, 36	9.693	0.004	0.212
	CON Post 53.9 (16.5)	Time*Group	1, 36	2.551	0.119	0.066
	INT Pre 57.2 (20.5)	Between	1, 36	8.841	0.005	0.197
	INT Post 72.05 (12.7)					
GasMed 30	CON Pre 41.42 (24.9)	main	1, 36	2.910	0.097	0.075
	CON Post 41.1 (21.2)	Time*Group	1, 36	3.242	0.08	0.083
	INT Pre 45.97 (19.2)	Between	1, 36	3.889	0.056	0.098
	INT Post 58.53 (15.8)					
GasMed 50	CON Pre 33.37 (19.1)	main	1, 36	0.685	0.413	0.019
	CON Post 33.53 (19.3)	Time*Group	1, 36	0.601	0.443	0.016
	INT Pre 38.37 (19.1)	Between	1, 36	2.401	0.130	0.063
	INT Post 43.1 (9.3)					
GasMed IC to MKF	CON Pre 33.05 (11.1)	main	1, 36	6.206	0.017	0.147
	CON Post 33.08 (14.1)	Time*Group	1, 36	6.137	0.018	0.146
	INT Pre 33.9 (13.5)	Between	1, 36	3.448	0.072	0.087
	INT Post 43.97 (6.1)					
GasMed Time to peak	CON Pre -0.1216 (0.08)	main	1, 36	3.476	0.07	0.088
	CON Post -0.1099 (0.06)	Time*Group	1, 36	0.779	0.383	0.021
	INT Pre -0.1173 (0.07)	Between	1, 36	0.549	0.464	0.015
	INT Post -0.0845 (0.07)					
GasLat 100	CON Pre 52.33 (15.1)	main	1, 36	6.804	0.013	0.159
	CON Post 53.33 (16.3)	Time*Group	1, 36	5.126	0.03	0.125
	INT Pre 57.66 (18.7)	Between	1, 36	7.658	0.009	0.175
	INT Post 71.81 (13.1)					
GasLat 30	CON Pre 43.81 (23.1)	main	1, 36	2.235	0.144	0.058
	CON Post 46.42 (23.6)	Time*Group	1, 36	0.725	0.4	0.02
	INT Pre 50.37 (20.2)	Between	1, 36	3.369	0.075	0.086
	INT Post 59.89 (16.7)					
GasLat 50	CON Pre 35.46 (20.8)	main	1, 36	2.993	0.092	0.077
	CON Post 39.26 (20.4)	Time*Group	1, 36	0.392	0.535	0.011
	INT Pre 38.02 (18.1)	Between	1, 36	0.962	0.333	0.026
	INT Post 46.14 (13.0)					
GasLat IC to MKF	CON Pre 34.0 (14.1)	Main	1, 36	5.718	0.22	0.137
	CON Post 47.39 (9.5)	Time*Group	1, 36	9.662	0.004	0.212
	INT Pre 51.24 (9.2)	Between	1, 36	15.275	0.000	0.298
	INT Post 49.49 (9.5)					
GasLat Time to peak	CON Pre -0.1063 (0.08)	main	1, 36	0.425	0.518	0.012
	CON Post -0.1030 (0.07)	Time*Group	1, 36	0.143	0.708	0.004
	INT Pre -0.0898 (0.08)	Between	1, 36	1.067	0.309	0.029
	INT Post -0.0775 (0.07)					
HamMed 100	CON Pre 54.78 (16.0)	main	1, 36	0.488	0.489	0.013
	CON Post 52.6 (16.9)	Time*Group	1, 36	1.744	0.195	0.046
	INT Pre 57.78 (16.1)	Between	1, 36	5.134	0.03	0.125
	INT Post 64.83 (9.9)					
HamMed 30	CON Pre 48.88 (20.5)	main	1, 36	0.174	0.679	0.005
	CON Post 54.48 (21.4)	Time*Group	1, 36	0.880	0.354	0.024
	INT Pre 56.3 (21.2)	Between	1, 36	0.534	0.470	0.015
	INT Post 54.17 (15.0)					
HamMed 50	CON Pre 38.37 (12.8)	main	1, 36	0.205	0.653	0.006
	CON Post 45.87 (16.6)	Time*Group	1, 36	3.287	0.078	0.084
	INT Pre 50.9 (19.7)	Between	1, 36	2.469	0.125	0.064
	INT Post 46.4 (15.3)					
HamMed IC to MKF	CON Pre 42.73 (8.1)	main	1, 36	0.333	0.567	0.009
	CON Post 46.37 (11.5)	Time*Group	1, 36	1.852	0.182	0.049
	INT Pre 44.85 (11.8)	Between	1, 36	0.027	0.870	0.001
	INT Post 43.38 (7.5)					
HamMed Time to peak	CON Pre -0.1749 (0.06)	main	1, 36	3.302	0.078	0.084
	CON Post -0.1449 (0.06)	Time*Group	1, 36	0.000	0.993	0.000
	INT Pre -0.1578 (0.06)	Between	1, 36	1.386	0.247	0.037
	INT Post -0.1275 (0.08)					
HamLat 100	CON Pre 58.79 (10.3)	main	1, 36	1.8	0.188	0.048
	CON Post 59.85 (13.4)	Time*Group	1, 36	0.666	0.420	0.018
	INT Pre 60.39 (13.0)	Between	1, 36	0.939	0.339	0.025
	INT Post 64.73 (11.1)					
HamLat 30	CON Pre 59.34 (15.5)	main	1, 36	1.172	0.286	0.032
	CON Post 60.14 (19.7)	Time*Group	1, 36	0.711	0.405	0.019
	INT Pre 58.98 (19.5)	Between	1, 36	0.292	0.593	0.008

	INT Post 65.42 (14.3)					
HamLat 50	CON Pre 41.31 (12.4) CON Post 50.7 (21.1) INT Pre 52.43 (18.5) INT Post 50.07 (14.8)	main Time*Group Between	1, 36 1, 36 1, 36	0.991 2.782 1.524	0.326 0.104 0.225	0.027 0.072 0.041
HamLat IC to MKF	CON Pre 49.07 (10.3) CON Post 49.47 (8.5) INT Pre 49.95 (11.4) INT Post 56.05 (8.0)	main Time*Group Between	1, 36 1, 36 1, 36	2.621 2.016 2.405	0.114 0.164 0.130	0.068 0.053 0.063
HamLat Time to peak	CON Pre -0.1674 (0.05) CON Post -0.1567 (0.06) INT Pre -0.1563 (0.07) INT Post -0.1449 (0.06)	main Time*Group Between	1, 36 1, 36 1, 36	0.816 0.001 0.492	0.372 0.980 0.487	0.022 0.000 0.013
VM 100	CON Pre 62.1 (16.9) CON Post 58.34 (14.7) INT Pre 56.97 (14.7) INT Post 59.37 (14.3)	main Time*Group Between	1, 36 1, 36 1, 36	0.081 1.694 0.220	0.777 0.201 0.642	0.002 0.045 0.006
VM 30	CON Pre 63.43 (20.8) CON Post 64.73 (21.7) INT Pre 65.90 (22.3) INT Post 66.47 (18.5)	main Time*Group Between	1, 36 1, 36 1, 36	0.054 0.008 0.151	0.818 0.929 0.700	0.001 0.000 0.004
VM50	CON Pre 59.12 (19.2) CON Post 58.6 (22.5) INT Pre 57.58 (22.3) INT Post 62.67 (20.1)	main Time*Group Between	1, 36 1, 36 1, 36	0.406 0.624 0.048	0.528 0.435 0.828	0.011 0.017 0.001
VM IC to MKF	CON Pre 47.22 (10.4) CON Post 47.26 (12.2) INT Pre 45.36 (13.3) INT Post 51.65 (10.5)	main Time*Group Between	1, 36 1, 36 1, 36	3.673 185.67 0.138	0.063 0.066 0.712	0.093 0.091 0.004
VM Time to peak	CON Pre -0.689 (0.09) CON Post -0.0789 (0.06) INT Pre -0.076 (0.09) INT Post -0.0574 (0.06)	main Time*Group Between	1, 36 1, 36 1, 36	0.113 1.112 0.107	0.739 0.299 0.745	0.003 0.03 0.003
VL 100	CON Pre 63.03 (18.7) CON Post 63.68 (12.0) INT Pre 61.19 (14.8) INT Post 64.33 (12.1)	main Time*Group Between	1, 36 1, 36 1, 36	0.425 0.184 0.026	0.519 0.671 0.873	0.012 0.005 0.001
VL 30	CON Pre 63.1 (18.3) CON Post 66.7 (18.6) INT Pre 64.58 (19.7) INT Post 70.42 (15.8)	main Time*Group Between	1, 36 1, 36 1, 36	1.431 0.08 0.352	0.239 0.779 0.556	0.038 0.002 0.01
VL 50	CON Pre 49.3 (17.6) CON Post 54.95 (19.1) INT Pre 49.3 (17.3) INT Post 57.83 (14.2)	main Time*Group Between	1, 36 1, 36 1, 36	4.643 0.197 0.101	0.038 0.660 0.752	0.114 0.005 0.003
VL IC to MKF	CON Pre 42.55 (6.9) CON Post 42.23 (9.8) INT Pre 41.72 (11.2) INT Post 51.83 (10.0)	main Time*Group Between	1, 36 1, 36 1, 36	7.392 8.36 2.9	0.01 0.006 0.097	0.170 0.188 0.075
VL Time to peak	CON Pre -0.0491 (0.1) CON Post -0.0673 (0.09) INT Pre -0.049 (0.08) INT Post -0.0551 (0.06)	main Time*Group Between	1, 36 1, 36 1, 36	0.778 0.192 0.074	0.384 0.664 0.788	0.021 0.005 0.002
RF 100	CON Pre 60.31 (16.1) CON Post 54.52 (10.5) INT Pre 50.69 (11.7) INT Post 55.75 (14.4)	main Time*Group Between	1, 36 1, 36 1, 36	0.031 6.841 1.209	0.861 0.013 0.279	0.001 0.160 0.032
RF 30	CON Pre 64.12 (18.4) CON Post 59.1 (17.2) INT Pre 57.76 (18.5) INT Post 59.56 (17.0)	main Time*Group Between	1, 36 1, 36 1, 36	0.209 0.936 0.419	0.651 0.340 0.522	0.006 0.025 0.012
RF 50	CON Pre 49.71 (13.8) CON Post 52.6 (17.9) INT Pre 51.2 (17.0) INT Post 53.98 (12.7)	main Time*Group Between	1, 36 1, 36 1, 36	0.964 0.001 0.124	0.333 0.978 0.727	0.026 0.000 0.003
RF IC to MKF	CON Pre 40.59 (6.0) CON Post 43.3 (11.6) INT Pre 43.5 (13.1) INT Post 44.99 (8.9)	main Time*Group Between	1, 36 1, 36 1, 36	1.182 0.093 0.710	0.284 0.762 0.405	0.032 0.03 0.019
RF Time to peak	CON Pre -0.0499 (0.07) CON Post -0.0644 (0.08)	main Time*Group	1, 36 1, 36	0.175 2.115	0.678 0.155	0.005 0.055

	INT Pre -0.0703 (0.08) INT Post -0.0441 (0.06)	Between	1, 36	0.00	1.00	0.000
GMed 100	CON Pre 55.74 (14.3) CON Post 55.93 (18.5) INT Pre 53.47 (17.0) INT Post 55.11 (12.1)	main Time*Group Between	1, 36 1, 36 1, 36	0.07 0.044 0.173	0.793 0.836 0.680	0.002 0.001 0.005
GMed 30	CON Pre 54.25 (18.3) CON Post 52.66 (18.7) INT Pre 53.06 (18.9) INT Post 54.33 (16.3)	main Time*Group Between	1, 36 1, 36 1, 36	0.002 0.175 0.002	0.962 0.678 0.961	0.000 0.005 0.000
GMed 50	CON Pre 50.14 (17.6) CON Post 52.82 (16.8) INT Pre 58.2 (17.1) INT Post 58.84 (15.7)	main Time*Group Between	1, 36 1, 36 1, 36	0.283 0.111 2.451	0.598 0.741 0.126	0.008 0.003 0.064
GMed IC to MKF	CON Pre 24.16 (11.8) CON Post 28.3 (13.0) INT Pre 30.47 (12.8) INT Post 38.78 (9.3)	main Time*Group Between	1, 36 1, 36 1, 36	15.411 1.730 5.820	0.000 0.197 0.021	0.300 0.046 0.139
GMed Time to peak	CON Pre -0.1308 (0.08) CON Post -0.1462 (0.05) INT Pre -0.1408 (0.05) INT Post -0.1054 (0.06)	main Time*Group Between	1, 36 1, 36 1, 36	0.532 3.451 1.033	0.471 0.071 0.316	0.015 0.087 0.028
GMax 100	CON Pre 54.59 (14.5) CON Post 56.0 (14.3) INT Pre 51.3 (15.8) INT Post 52.54 (15.5)	main Time*Group Between	1, 36 1, 36 1, 36	0.132 0.001 1.019	0.719 0.976 0.319	0.004 0.000 0.028
GMax 30	CON Pre 54.47 (17.9) CON Post 54.54 (18.8) INT Pre 53.2 (19.1) INT Post 55.32 (20.1)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.061 0.054 0.003	0.806 0.818 0.955	0.002 0.001 0.000
GMax 50	CON Pre 55.32 (16.4) CON Post 56.18 (15.4) INT Pre 54.76 (14.7) INT Post 61.36 (18.5)	main Time*Group Between	1, 36 1, 36 1, 36	1.181 0.699 0.326	0.284 0.409 0.571	0.032 0.019 0.009
GMax IC to MKF	CON Pre 33.05 (11.1) CON Post 33.08 (14.1) INT Pre 33.9 (13.5) INT Post 43.97 (6.1)	main Time*Group Between	1, 36 1, 36 1, 36	0.397 0.349 3.141	0.533 0.558 0.085	0.011 0.01 0.08
GMax Time to peak	CON Pre -0.1428 (0.7) CON Post -0.138 (0.05) INT Pre -0.1205 (0.06) INT Post -0.936 (0.05)	main Time*Group Between	1, 36 1, 36 1, 36	1.340 0.648 6.830	0.255 0.426 0.013	0.036 0.018 0.159

Hop and twist Kinematics and Kinetics

Variable	Descriptives	Statistic	df	F	Sig	Effect size
Trunk – Flexion	CON Pre 172.69 (5.2) CON Post 171.96 (4.5) INT Pre 171.5 (4.7) INT Post 171.8 (5.3)	main Time*Group Between	1, 36 1, 36 1, 36	0.052 0.318 0.259	0.821 0.576 0.614	0.001 0.009 0.007
Trunk – Lat Flexion	CON Pre 6.26 (4.0) CON Post 5.67 (4.5) INT Pre 4.89 (4.2) INT Post 6.1 (3.9)	main Time*Group Between	1, 36 1, 36 1, 36	0.405 3.385 0.139	0.529 0.074 0.711	0.011 0.086 0.004
Trunk Rotation	CON Pre 9.14 (8.2) CON Post 9.22 (6.5) INT Pre 6.19 (7.6) INT Post 6.52 (7.3)	main Time*Group Between	1, 36 1, 36 1, 36	0.053 0.02 1.599	0.819 0.888 0.214	0.001 0.001 0.043
Max Lat Flexion	CON Pre -2.42 (7.9) CON Post -3.15 (7.2) INT Pre -3.30 (7.2) INT Post -3.38 (7.3)	main Time*Group Between	1, 36 1, 36 1, 36	0.127 0.023 0.102	0.724 0.881 0.751	0.004 0.001 0.003
Lat C of G	CON Pre 0.009 (0.02) CON Post 0.014 (0.01) INT Pre 0.20 (0.02) INT Post 0.016 (0.019)	main Time*Group Between	1, 36 1, 36 1, 36	0.075 2.507 1.678	0.785 0.122 0.203	0.002 0.065 0.045
Hip – Flexion	CON Pre 16.17 (4.9) CON Post 15.54 (5.9) INT Pre 16.49 (6.8) INT Post 14.46 (6.7)	Within – main Time*Group Between	1, 36 1, 36 1, 36	1.889 0.524 0.047	0.178 0.474 0.829	0.05 0.014 0.001
Hip – Lat Flexion	CON Pre -4.22 (3.6) CON Post -4.33 (4.6) INT Pre -4.54 (2.8) INT Post -4.42 (4.4)	main Time*Group Between	1, 36 1, 36 1, 36	0.000 0.039 0.033	0.992 0.844 0.858	0.000 0.000 0.001
Hip – Axial Rotation	CON Pre 7.15 (9.9) CON Post 3.82 (7.4) INT Pre 5.81 (5.5) INT Post 4.07 (6.93)	main Time*Group Between	1, 36 1, 36 1, 36	3.345 0.329 0.72	0.076 0.570 0.789	0.085 0.009 0.002
Knee – Flexion	CON Pre 11.6 (4.3) CON Post 12.66 (5.6) INT Pre 10.44 (4.9) INT Post 10.54 (5.2)	main Time*Group Between	1, 36 1, 36 1, 36	1.151 0.780 1.123	0.292 0.383 0.296	0.031 0.021 0.03
Knee – frontal plane motion	CON Pre -2.9 (3.5) CON Post -2.94 (3.5) INT Pre -2.17 (3.2) INT Post -2.94 (3.5)	main Time*Group Between	1, 36 1, 36 1, 36	0.388 0.284 0.280	0.537 0.598 0.600	0.011 0.008 0.008
Knee – Axial Rotation	CON Pre 1.67 (9.5) CON Post 5.0 (7.5) INT Pre 5.3 (6.4) INT Post 5.61 (7.4)	main Time*Group Between	1, 36 1, 36 1, 36	2.230 1.479 0.899	0.144 0.232 0.349	0.058 0.039 0.024
Max Knee Adduction	CON Pre 0.37 (1.8) CON Post 0.68 (1.9) INT Pre 0.65 (1.5) INT Post -0.43	main Time*Group Between	1, 36 1, 36 1, 36	1.160 3.861 0.883	0.289 0.057 0.354	0.031 0.097 0.024
Max Knee Abduction	CON Pre 9.04 (2.8) CON Post 7.45 (2.8) INT Pre 8.04 (2.5) INT Post 7.03 (1.8)	main Time*Group Between	1, 36 1, 36 1, 36	6.575 0.325 1.303	0.015 0.570 0.261	0.154 0.009 0.035
Knee Excursion	CON Pre 9.3 (2.5) CON Post 7.94 (1.6) INT Pre 8.42 (2.0) INT Post 6.66 (1.6)	main Time*Group Between	1, 36 1, 36 1, 36	25.551 0.383 3.861	0.000 0.540 0.057	0.415 0.011 0.097
Ankle – Flexion	CON Pre 45.66 (6.4) CON Post 47.96 (8.7) INT Pre 49.58 (7.9) INT Post 50.36 (6.7)	main Time*Group Between	1, 36 1, 36 1, 36	3.790 0.924 1.892	0.059 0.343 0.177	0.095 0.025 0.05
Ankle – Lat Flexion	CON Pre -7.25 (5.0) CON Post -6.27 (6.9) INT Pre -8.73 (7.3) INT Post -10.44 (7.9)	main Time*Group Between	1, 36 1, 36 1, 36	0.139 1.916 1.946	0.714 0.175 0.172	0.004 0.051 0.051
Ankle - Rotation	CON Pre -14.17 (6.74) CON Post -12.79 (7.77) INT Pre -11.67 (5.75) INT Post -13.59 (6.86)	main Time*Group Between	1, 36 1, 36 1, 36	0.977 3.701 0.017	0.330 0.062 0.898	0.026 0.093 0.000

Peak vGRF	CON Pre 1514.3 (249.8) CON Post 1520.0 (272.4) INT Pre 1613.1 (260.9) INT Post 1495.0 (191.3)	main Time*Group Between	1, 36 1, 36 1, 36	4.725 5.737 0.241	0.036 0.022 0.626	0.116 0.137 0.007
Norm vGRF	CON Pre 2.51 (0.32) CON Post 2.49 (0.42) INT Pre 2.51 (0.375) INT Post 2.33 (0.3)	main Time*Group Between	1, 36 1, 36 1, 36	4.799 3.069 0.515	0.035 0.088 0.478	0.118 0.079 0.014
RFD	CON Pre 10.90 (1.2) CON Post 11.3 (1.5) INT Pre 11.43 (2.0) INT Post 10.56 (1.1)	main Time*Group Between	1, 36 1, 36 1, 36	1.293 9.321 0.05	0.263 0.004 0.824	0.035 0.206 0.001
Hop height	CON Pre 0.165 (0.04) CON Post 0.168 (0.04) INT Pre 0.1595 (0.04) INT Post 0.1545 (0.03)	main Time*Group Between	1, 36 1, 36 1, 36	0.064 0.524 0.688	0.802 0.466 0.412	0.002 0.015 0.019
Trunk flexion MKF	CON Pre 171.18 (5.5) CON Post 172.26 (5.4) INT Pre 172.58 (5.3) INT Post 172.0 (4.9)	main Time*Group Between	1, 36 1, 36 1, 36	0.670 0.126 0.563	0.418 0.724 0.458	0.018 0.003 0.015
Trunk frontal plane motion MKF	CON Pre -15.51 (4.4) CON Post -2.26 (5.1) INT Pre -1.93 (4.7) INT Post -2.13 (5.8)	main Time*Group Between	1, 36 1, 36 1, 36	0.352 0.123 0.01	0.557 0.728 0.921	0.01 0.003 0.00
Trunk axial rotation MKF	CON Pre 6.08 (4.2) CON Post 5.66 (6.0) INT Pre 5.4 (7.4) INT Post 4.47 (6.7)	main Time*Group Between	1, 36 1, 36 1, 36	0.607 0.089 0.263	0.441 0.077 0.611	0.007 0.002 0.007
Hip flexion MKF	CON Pre 36.18 (9.6) CON Post 34.96 (9.4) INT Pre 34.1 (9.3) INT Post 34.9 (11.9)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.024 0.608 0.125	0.877 0.441 0.726	0.001 0.017 0.003
Hip frontal plane motion MKF	CON Pre 2.65 (5.6) CON Post 1.85 (3.6) INT Pre 1.85 (3.6) INT Post 2.18 (5.1)	main Time*Group Between	1, 36 1, 36 1, 36	0.991 1.96 0.058	0.326 0.170 0.811	0.027 0.052 0.002
Hip axial rotation MKF	CON Pre 8.08 (9.7) CON Post 4.47 (7.3) INT Pre 5.9 (7.0) INT Post 4.05 (6.3)	main Time*Group Between	1, 36 1, 36 1, 36	4.221 0.441 0.382	0.047 0.511 0.541	0.047 0.012 0.01
Knee flexion MKF	CON Pre -44.3 (10.8) CON Post -45.12 (10.1) INT Pre -41.2 (7.2) INT Post -42.19 (10.1)	main Time*Group Between	1, 36 1, 36 1, 36	0.506 0.003 1.098	0.481 0.957 0.302	0.014 0.000 0.03
Knee frontal plane motion MKF	CON Pre 4.73 (4.9) CON Post 2.62 (5.3) INT Pre 3.24 (5.8) INT Post 2.33 (5.1)	main Time*Group Between	1, 36 1, 36 1, 36	4.529 0.703 0.318	0.04 0.407 0.576	0.112 0.019 0.009
Knee axial rotation MKF	CON Pre -0.77 (7.2) CON Post 2.45 (6.5) INT Pre 0.74 (6.9) INT Post -0.67 (7.8)	main Time*Group Between	1, 36 1, 36 1, 36	0.827 5.421 0.15	0.369 0.026 0.700	0.022 0.131 0.004
Ankle flexion MKF	CON Pre 93.75 (6.7) CON Post 94.90 (5.2) INT Pre 93.65 (6.2) INT Post 94.9 (5.2)	main Time*Group Between	1, 36 1, 36 1, 36	1.09 0.118 0.016	0.303 0.733 0.901	0.029 0.003 0.00
Ankle frontal plane motion MKF	CON Pre -27.8 (6.5) CON Post -24.47 (7.0) INT Pre -27.1 (10.4) INT Post -25.94 (6.9)	main Time*Group Between	1, 36 1, 36 1, 36	2.641 0.605 0.032	0.113 0.442 0.859	0.068 0.017 0.001
Ankle axial rotation MKF	CON Pre -4.43 (3.8) CON Post -3.72 (4.6) INT Pre -4.05 (3.3) INT Post -4.96 (4.6)	main Time*Group Between	1, 36 1, 36 1, 36	0.015 0.913 0.173	0.904 0.341 0.68	0.00 0.025 0.05

Study 3 Stats table – Sidecut - EMG

Variable	Descriptive (SD)	Statistic	df df	F	P Significance	Effect size
GasMed 100	CON Pre 19.1 (13.3) Con Post 22.1 (13.6) INT Pre 25.3 (12.6) INT Post 31.27 (11.4)	Within – main Time*Group Between	1, 36 1, 36 1, 36	5.336 0.588 4.441	0.027 0.448 0.042	0.129 0.016 0.110
GasMed 30	CON Pre 18.28 (11.6) Con Post 23.1 (16.7) INT Pre 25.25 (14.9) INT Post 28.4 (11.9)	Within – main Time*Group Between	1, 36 1, 36 1, 36	2.842 0.127 2.513	0.1 0.723 0.122	0.073 0.004 0.065
GasMed 50	CON Pre 19.9 (11.7) Con Post 20.19 (10.4) INT Pre 25.03 (11.1) INT Post 28.77 (10.8)	Within – main Time*Group Between	1, 36 1, 36 1, 36	1.037 0.76 5.339	0.315 0.389 0.027	0.028 0.021 0.129
GasMed IC to MKF	CON Pre 42.06 (11.2) Con Post 46.44 (8.5) INT Pre 45.06 (7.8) INT Post 53.07 (7.8)	Within – main Time*Group Between	1, 36 1, 36 1, 36	10.277 0.882 5.05	0.003 0.354 0.031	0.222 0.024 0.123
GasMed Time to peak	CON Pre -0.1229 (0.04) Con Post -0.1251 (0.03) INT Pre -0.1119 (0.03) INT Post -0.1149 (0.03)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.158 0.004 2.407	0.693 0.949 0.130	0.004 0.000 0.063
GasLat 100	CON Pre 16.38 (10.1) Con Post 22.42 (13.7) INT Pre 22.97 (11.04) INT Post 29.85 (12.3)	Within – main Time*Group Between	1, 36 1, 36 1, 36	10.287 0.044 4.555	0.003 0.836 0.04	0.222 0.001 0.112
GasLat 30	CON Pre 17.89 (9.9) Con Post 24.02 (15.0) INT Pre 27.13 (15.2) INT Post 25.87 (9.9)	Within – main Time*Group Between	1, 36 1, 36 1, 36	1.159 2.672 2.557	0.289 0.111 0.119	0.031 0.069 0.066
GasLat 50	CON Pre 18.7 (10.2) Con Post 20.8 (10.5) INT Pre 24.06 (12.4) INT Post 28.28 (8.0)	Within – main Time*Group Between	1, 36 1, 36 1, 36	1.844 0.210 6.893	0.183 0.649 0.013	0.049 0.006 0.161
GasLat IC to MKF	CON Pre 41.32 (11.3) Con Post 46.6 (8.1) INT Pre 46.54 (10.01) INT Post 52.89 (7.8)	Within – main Time*Group Between	1, 36 1, 36 1, 36	6.009 0.051 8.869	0.019 0.822 0.005	0.143 0.001 0.198
GasLat Time to peak	CON Pre -0.1203 (0.032) Con Post -0.1209 (0.028) INT Pre -0.1222 (0.03) INT Post -0.1168 (0.03)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.196 0.308 0.022	0.66 0.582 0.883	0.005 0.008 0.001
HamMed 100	CON Pre 28.5 (7.1) Con Post 28.0 (12.9) INT Pre 31.4 (13) INT Post 28.88 (8.8)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.551 0.231 0.437	0.463 0.634 0.513	0.015 0.006 0.012
HamMed 30	CON Pre 35.9 (11.5) Con Post 34.2 (18.6) INT Pre 35.7 (15.1) INT Post 31 (9.9)	Within – main Time*Group Between	1, 36 1, 36 1, 36	1.149 0.262 0.238	0.291 0.612 0.628	0.031 0.007 0.007
HamMed 50	CON Pre 37.2 (11.6) Con Post 31.01 (8.3) INT Pre 37.77 (11.5) INT Post 34.53 (9.8)	Within – main Time*Group Between	1, 36 1, 36 1, 36	5.116 0.504 0.581	0.03 0.482 0.451	0.124 0.014 0.016
HamMed IC to MKF	CON Pre 54.94 (11.8) Con Post 55.33 (11.8) INT Pre 56.96 (10.6) INT Post 59.79 (9.0)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.553 0.313 1.363	0.462 0.579 0.251	0.015 0.009 0.036
HamMed Time to peak	CON Pre -0.1321 (0.03) Con Post -0.1383 (0.4) INT Pre -0.1344 (0.03) INT Post -0.1197 (0.03)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.331 2.027 0.958	0.569 0.163 0.334	0.009 0.053 0.026
HamLat 100	CON Pre 29.07 (10.2) Con Post 30.5 (17.0) INT Pre 32.27 (9.9) INT Post 33.05 (11.3)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.136 0.014 0.927	0.683 0.906 0.342	0.005 0.000 0.025
HamLat 30	CON Pre 29.07 (10.2) Con Post 30.5 (17.0) INT Pre 32.3 (9.9) INT Post 33.05 (11.3)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.065 0.000 0.378	0.800 0.997 0.378	0.002 0.000 0.022

HamLat 50	CON Pre 35.57 (11.1) Con Post 33.36 (9.9) INT Pre 35.53 (12.2) INT Post 35.60 (9.6)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.293 0.333 0.146	0.592 0.567 0.705	0.008 0.009 0.004
HamLat IC to MKF	CON Pre 49.38 (13) Con Post 54.30 (10.7) INT Pre 51.7 (10) INT Post 55.88 (7.5)	Within – main Time*Group Between	1, 36 1, 36 1, 36	5.036 0.033 0.552	0.031 0.856 0.475	0.123 0.001 0.014
HamLat Time to peak	CON Pre -0.1478 (0.04) Con Post -0.139 (0.07) INT Pre -0.1575 (0.06) INT Post -0.1159 (0.05)	Within – main Time*Group Between	1, 36 1, 36 1, 36	4.4448 1.886 0.298	0.042 0.178 0.589	0.05 0.05 0.008
VM 100	CON Pre 31.76 (10.6) Con Post 36.85 (16) INT Pre 43.6 (15) INT Post 50.1 (14.8)	Within – main Time*Group Between	1, 36 1, 36 1, 36	4.711 0.07 0.927	0.037 0.793 0.03	0.005 0.000 0.025
VM 30	CON Pre 29.83 (8.4) Con Post 34.75 (14.4) INT Pre 36.94 (15.8) INT Post 40.57 (10.8)	Within – main Time*Group Between	1, 36 1, 36 1, 36	2.882 0.065 3.864	0.098 0.800 0.057	0.074 0.002 0.097
VM 50	CON Pre 40.32 (10.9) Con Post 39.89 (11.9) INT Pre 43.79 (12.6) INT Post 41.22 (13.6)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.331 0.169 0.622	0.569 0.683 0.436	0.009 0.005 0.017
VM IC to MKF	CON Pre 57.15 (9.2) Con Post 57.86 (8.2) INT Pre 58.3 (8.6) INT Post 60.52 (6.3)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.756 0.200 0.883	0.390 0.657 0.354	0.021 0.006 0.024
VM Time to peak	CON Pre -0.1227 (0.04) Con Post -0.1324 (0.4) INT Pre -0.1106 (0.04) INT Post -0.119 (0.03)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.113 0.577 3.678	0.738 0.452 0.063	0.003 0.016 0.093
VL 100	CON Pre 30.19 (10.5) Con Post 29.7 (11.8) INT Pre 41.4 (14.5) INT Post 39.82 (14.9)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.206 0.057 8.697	0.653 0.812 0.006	0.006 0.002 0.195
VL 30	CON Pre 32.1 (12.5) Con Post 31.5 (14.2) INT Pre 40.56 (14.4) INT Post 36.1 (12.5)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.991 0.575 3.378	0.326 0.453 0.074	0.027 0.016 0.086
VL 50	CON Pre 32.41 (13.9) Con Post 29.79 (10.6) INT Pre 39.19 (15.9) INT Post 35.9 (12.6)	Within – main Time*Group Between	1, 36 1, 36 1, 36	1.106 0.014 3.75	0.300 0.907 0.061	0.03 0.000 0.094
VL IC to MKF	CON Pre 50.32 (11.5) Con Post 48.9 (5.8) INT Pre 50.4 (14.8) INT Post 53.3 (8.0)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.101 0.871 0.754	0.752 0.357 0.391	0.003 0.024 0.021
VL Time to peak	CON Pre -0.1113 (0.03) Con Post -0.1151 (0.03) INT Pre -0.1044 (0.05) INT Post -0.0933 (0.02)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.250 1.064 2.883	0.620 0.309 0.098	0.007 0.029 0.074
RF 100	CON Pre 29.6 (10.6) Con Post 28.03 (10.4) INT Pre 32.7 (11.4) INT Post 35.08 (12.4)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.029 0.741 3.2	0.867 0.395 0.082	0.001 0.02 0.082
RF 30	CON Pre 27.66 (10.2) Con Post 29.37 (10.6) INT Pre 33.9 (15.4) INT Post 31.59 (13.6)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.014 0.608 1.691	0.906 0.441 0.202	0.000 0.017 0.045
RF 50	CON Pre 35.06 (13.8) Con Post 32.44 (14.4) INT Pre 38.01 (13.9) INT Post 36.07 (14.7)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.596 0.011 0.865	0.445 0.917 0.359	0.016 0.000 0.023
RF IC to MKF	CON Pre 49.35 (9.9) Con Post 49.22 (6.7) INT Pre 51.03 (8.1) INT Post 54.62 (7.9)	Within – main Time*Group Between	1, 36 1, 36 1, 36	1.096 1.279 2.788	0.302 0.265 0.104	0.03 0.034 0.072
RF Time to peak	CON Pre -0.1179 (0.3) Con Post -0.1066 (0.2)	Within – main Time*Group	1, 36 1, 36	0.412 1.069	0.525 0.308	0.011 0.029

	INT Pre -0.0958 (0.2) INT Post -0.0985 (0.3)	Between	1, 36	4.704	0.037	0.116
GMed 100	CON Pre 23.2 (5.8) Con Post 19.7 (7.1) INT Pre 25.66 (9.6) INT Post 22.3 (5.9)	Within – main Time*Group Between	1, 36 1, 36 1, 36	4.699 0.01 2.0	0.037 0.974 0.165	0.115 0.000 0.053
GMed 30	CON Pre 24.7 (7.1) Con Post 22.1 (8.4) INT Pre 27.94 (11.67) INT Post 21.87 (6.1)	Within – main Time*Group Between	1, 36 1, 36 1, 36	6.759 6.759 0.433	0.013 1.09 0.515	0.158 0.29 0.012
GMed 50	CON Pre 18.89 (11.7) Con Post 22.13 (8.4) INT Pre 25.03 (11.1) INT Post 21.99 (7.2)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.04 1.338 1.418	0.842 0.255 0.242	0.001 0.036 0.038
GMed IC to MKF	CON Pre 35.33 (5.2) Con Post 37.14 (7.8) INT Pre 40.69 (9.8) INT Post 38.85 (7.8)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.000 0.991 3.308	0.995 0.326 0.077	0.000 0.027 0.084
GMed Time to peak	CON Pre -0.1259 (0.03) Con Post -0.1269 (0.03) INT Pre -0.1223 (0.03) INT Post -0.1141 (0.02)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.339 0.539 0.539	0.564 0.468 0.468	0.009 0.015 0.015
GMax 100	CON Pre 22.29 (7.2) Con Post 21.89 (8.1) INT Pre 27.24 (12.8) INT Post 25.52 (11.0)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.286 0.113 2.653	0.596 0.739 0.112	0.008 0.003 0.069
GMax 30	CON Pre 27.99 (9.8) Con Post 24.44 (9.6) INT Pre 29.17 (12.6) INT Post 24.96 (12.0)	Within – main Time*Group Between	1, 36 1, 36 1, 36	3.577 0.025 0.081	0.067 0.875 0.778	0.09 0.001 0.002
GMax 50	CON Pre 19.90 (11.7) Con Post 20.51 (10.1) INT Pre 25.03 (11.1) INT Post 28.99 (10.6)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.378 0.92 6.849	0.542 0.763 0.026	0.01 0.03 0.13
GMax IC to MKF	CON Pre 40.67 (8.4) Con Post 41.86 (6.9) INT Pre 43.05 (10.0) INT Post 45.26 (18.9)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.79 0.075 1.914	0.38 0.786 0.175	0.021 0.002 0.05
Gmax Time to peak	CON Pre -0.1386 (0.6) Con Post -0.1266 (0.04) INT Pre -0.131 (0.04) INT Post -0.1185 (0.02)	Within – main Time*Group Between	1, 36 1, 36 1, 36	2.938 0.001 0.543	0.095 0.972 0.466	0.075 0.000 0.015

Sidecut Kinematics and Kinetics

Variable	Descriptives	Statistic	df	F	Sig	Effect size
Trunk – Flexion IC	CON Pre 165.58 (5.5) Con Post 167.49 (5.6) INT Pre 166.94 (6.0) INT Post 166.64 (7.6)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.725 0.1.379 0.886	0.4 0.248 0.886	0.02 0.037 0.001
Trunk – Lat Flexion IC	CON Pre -1.42 (9.9) Con Post -2.25 (5.2) INT Pre -1.79 (5.6) INT Post -1.57 (3.5)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.186 0.541 0.014	0.669 0.467 0.908	0.005 0.015 0.00
Trunk Rotation IC	CON Pre 0.28 (2.6) Con Post -0.38 (4.2) INT Pre -1.30 (4.3) INT Post -0.79 (3.9)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.009 0.729 0.602	0.924 0.399 0.443	0.000 0.02 0.016
Max Lat Flexion	CON Pre -11.37 (5.3) Con Post -13.73 (5.1) INT Pre -11.55 (5.6) INT Post -10.97 (5.0)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.896 2.423 0.826	0.350 0.128 0.369	0.024 0.063 0.022
Lat C of G IC to MKF	CON Pre -0.056 (0.1) Con Post -0.063 (0.02) INT Pre -0.056 (0.02) INT Post -0.058 (0.017)	Within – main Time*Group Between	1, 36 1, 36 1, 36	1.534 0.412 0.220	0.224 0.525 0.642	0.041 0.011 0.006
Hip – Flexion IC	CON Pre 38.86 (8.6) Con Post 37.85 (8.7) INT Pre 41.99 (9.8) INT Post 35.77 (8.7)	Within – main Time*Group Between	1, 36 1, 36 1, 36	7.139 3.713 0.035	0.011 0.062 0.853	0.165 0.093 0.01
Hip – Lat Flexion IC	CON Pre -12.74 (5.4) Con Post -10.87 (6.4) INT Pre -10.44 (4.9) INT Post -9.72 (5.4)	Within – main Time*Group Between	1, 36 1, 36 1, 36	2.685 0.533 1.148	0.110 0.47 0.291	0.069 0.015 0.031
Hip – Axial Rotation IC	CON Pre 7.72 (8.8) Con Post 3.6 (5.4) INT Pre 3.64 (6.6) INT Post 2.76 (8.1)	Within – main Time*Group Between	1, 36 1, 36 1, 36	3.257 1.359 1.612	0.079 0.251 0.212	0.083 0.036 0.043
Knee – Flexion IC	CON Pre -20.70 (6.7) Con Post -18.64 (8.4) INT Pre -19.28 (10.1) INT Post -17.96 (8.2)	Within – main Time*Group Between	1, 36 1, 36 1, 36	1.756 0.085 0.188	0.193 0.772 0.668	0.047 0.002 0.005
Knee – frontal plane motion IC	CON Pre -0.27 (4.5) Con Post -0.77 (4.9) INT Pre -1.01 (4.3) INT Post -1.9 (3.1)	Within – main Time*Group Between	1, 36 1, 36 1, 36	1.466 0.119 0.563	0.234 0.732 0.458	0.039 0.003 0.015
Knee – axial Rotation IC	CON Pre -2.22 (7.5) Con Post 0.08 (8.0) INT Pre 1.8 (8.2) INT Post 0.037 (6.2)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.097 1.839 1.393	0.758 0.184 0.246	0.003 0.049 0.037
Max Knee Add	CON Pre 0.06 (2.67) Con Post 0.75 (1.8) INT Pre 0.07 (1.7) INT Post -0.44 (1.8)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.134 1.466 1.644	0.716 0.234 0.208	0.004 0.039 0.044
Max Knee Abd	CON Pre 9.89 (3.45) Con Post 9.93 (3.2) INT Pre 10.89 (2.79) INT Post 8.47 (2.75)	Within – main Time*Group Between	1, 36 1, 36 1, 36	7.621 8.096 0.068	0.009 0.007 0.795	0.175 0.184 0.002
Knee Excursion	CON Pre 10.07 (1.7) Con Post 11.3 (2.77) INT Pre 10.79 (2.24) INT Post 8.04 (1.94)	Within – main Time*Group Between	1, 36 1, 36 1, 36	7.180 49.624 3.775	0.011 0.000 0.06	0.166 0.580 0.095
Ankle – flexion	CON Pre 69.78 (14.6) Con Post 72.97 (16.6) INT Pre 67.94 (13.1) INT Post 64.3 (11.1)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.007 2.766 1.602	0.936 0.105 0.214	0.000 0.071 0.043
Ankle – frontal plane motion	CON Pre -10.98 (6.2) Con Post -10.02 (6.5) INT Pre -10.48 (8.6) INT Post -9.76 (5.7)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.440 0.009 0.033	0.551 0.924 0.857	0.012 0.000 0.001
Ankle – axial rotation	CON Pre -20.26 (6.7) Con Post -18.16 (6.7) INT Pre -22.05 (7.2) INT Post -23.16 (8)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.224 2.423 2.645	0.639 0.128 0.113	0.006 0.063 0.068

Peak vGRF	CON Pre 1185.2 (212.6) Con Post 1226.3 (211.2) INT Pre 1226.7 (208.6) INT Post 1171.5 (180.5)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.042 1.984 0.014	0.838 0.168 0.907	0.001 0.052 0.000
Norm vGRF	CON Pre 1.97 (0.3) Con Post 1.98 (0.3) INT Pre 1.90 (0.3) INT Post 1.82 (0.2)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.408 0.852 2.779	0.527 0.362 0.104	0.011 0.023 0.072
RFD	CON Pre 19.53 (9.9) Con Post 21.75 (9.4) INT Pre 18.88 (9.1) INT Post 12.83 (5.71)	Within – main Time*Group Between	1, 36 1, 36 1, 36	2.476 11.519 3.593	0.124 0.002 0.066	0.064 0.242 0.091
Trunk flexion MKF	CON Pre 148.44 (8.5) Con Post 149.69 (9.8) INT Pre 153.03 (7.8) INT Post 151.86 (10.7)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.001 0.958 1.512	0.977 0.334 0.227	0.00 0.026 0.04
Trunk frontal plane motion MKF	CON Pre -7.87 (4.4) Con Post -10.47 (5.5) INT Pre -8.33 (5.9) INT Post -7.9 (5.5)	Within – main Time*Group Between	1, 36 1, 36 1, 36	1.347 2.6 0.510	0.253 0.116 0.48	0.036 0.067 0.014
Trunk axial rotation MKF	CON Pre -8.22 (5.4) Con Post -8.54 (7.3) INT Pre -7.78 (4.9) INT Post -8.3 (6.6)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.236 0.014 0.038	0.628 0.908 0.846	0.007 0.000 0.001
Hip flexion MKF	CON Pre 45.7 (11.7) Con Post 46.1 (11.0) INT Pre 45.2 (11.1) INT Post 38.79 (8.0)	Within – main Time*Group Between	1, 36 1, 36 1, 36	3.401 4.295 1.683	0.073 0.045 0.203	0.086 0.107 0.045
Hip frontal plane motion MKF	CON Pre -13.02 (7.3) Con Post -12.4 (7.2) INT Pre -11.4 (6.6) INT Post -10.4 (6.2)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.835 0.000 0.757	0.367 0.993 0.390	0.023 0.000 0.021
Hip axial rotation MKF	CON Pre 6.79 (7.7) Con Post 3.6 (5.4) INT Pre 5.04 (6.6) INT Post 2.76 (8.1)	Within – main Time*Group Between	1, 36 1, 36 1, 36	3.567 3.831 0.544	0.067 0.758 0.446	0.09 0.003 0.015
Knee flexion MKF	CON Pre -61.82 (7.2) Con Post -63.62 (6.9) INT Pre -61.98 (11.5) INT Post -63.6 (6.8)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.172 2.881 0.911	0.680 0.098 0.346	0.005 0.074 0.025
Knee frontal plane motion MKF	CON Pre -1.09 (6.7) Con Post -3.65 (7.1) INT Pre -3.81 (7.6) INT Post -5.68 (6.6)	Within – main Time*Group Between	1, 36 1, 36 1, 36	4.308 0.104 1.388	0.045 0.748 0.246	0.107 0.003 0.037
Knee axial rotation MKF	CON Pre 10.57 (5.2) Con Post 13.42 (6.4) INT Pre 10.81 (7.6) INT Post 9.3 (6.2)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.645 6.786 1.025	0.427 0.013 0.318	0.018 0.159 0.028
Ankle flexion MKF	CON Pre 91.81 (8.6) Con Post 94.39 (6.2) INT Pre 94.56 (7.6) INT Post 95.3 (5.4)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.650 0.957 0.197	0.425 0.334 0.197	0.018 0.026 0.046
Ankle frontal plane motion MKF	CON Pre -10.9 (6.1) Con Post -10.88 (8.1) INT Pre -11.46 (6.9) INT Post -12.16 (6.0)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.006 0.01 0.561	0.936 0.920 0.561	0.00 0.00 0.09
Ankle axial rotation MKF	CON Pre -23.11 (6.9) Con Post -21.3 (5.8) INT Pre -23.4 (5.8) INT Post -24.3 (6.1)	Within – main Time*Group Between	1, 36 1, 36 1, 36	0.153 1.377 1.057	0.698 0.248 0.311	0.004 0.037 0.029

Appendix 5.14 Participant consent

Edinburgh Napier
UNIVERSITY

CONSENT FORM FOR PARTICIPATION IN PHYSICAL ACTIVITIES

For your participation in a Sport and Exercise Science activity, you are asked to complete the form below regarding your current health. In accordance with the Data Protection Act 1998 all the information you provide will be held securely and treated in the strictest confidence. This information will be viewed only, not be shared with anyone else unless this is: with your agreement, required by law or to protect your vital interests.

Name: ....
Date of Birth……………. ....
Hockey Club/league playing in ....
Playing experience (in years)……………………………………………
Height: ……………….(m)
Weight: ……………….(kg)

GENERAL HEALTH INFORMATION

Look carefully at the following list and tick which symptoms apply to you. If you feel necessary please discuss with the experimenter whether you should exercise.

Allergies ☐
Asthma
Cold or flu like symptoms (past week) ☐
Epilepsy ☐
High Blood pressure ☐
Palpitations ☐
Other ☐

Arthritis/swollen, ☐
stiff or painful joints
Chest Pains / Discomfort ☐
Diabetes
Heart or Lung trouble ☐
Orthopaedic problems ☐
Shortness of breath ☐
None of the above

Have you been injured in the last 3 months Yes ☐ No ☐

If yes, please give details in the space below.

PLEASE READ THE FOLLOWING CAREFULLY:

If you suffer any unusual or any unexpected symptoms during the activity, **please stop immediately**. If you experience any such feelings once the experiment/test period is over, please consult the experimenter or, if they occur after class has finished, please consult your own doctor.

DECLARATION

I,……………………………………………………………………, volunteer to be participant in Sport and Exercise Science experiments.

I have read and understood the experiment descriptor provided and the experimenter has explained to my satisfaction the purpose of the experiment and possible risks involved.

I understand that it is my responsibility to advise the experimenter of any changes in my health during the course of the study.

I understand that I may withdraw from the activity at any time and that I am under no obligation to give reasons for withdrawal. Furthermore, I understand that my choice to participate in this experiment will neither be detrimental to nor further my position in any way.

Informed Consent Form

"The effects of a specific warm up on movement patterns and injury reduction"

I have read and understood the information sheet and this consent form. I have had an opportunity to ask questions about my participation. ☐

I understand that I am under no obligation to take part in this study ☐

I understand that I have the right to withdraw from this study at any stage without giving any reason ☐

I agree to participate in this study ☐

Name of participant: ____

Signature of participant: ____

Signature of researcher: ____

Date: __________________

Appendix 5.15 Variability Analysis

A summary of number of variables for each group in each category

		Control Group				**Intervention group**		
Variable	**Task**	**Greater***	**Less***	**Trivial***		**Greater**	**Less**	**Trivial**
EMG	**SH**	11	9	25		11	24	10
	HT	13	6	26		4	23	18
	USC	12	13	20		2	27	16
Kinematics	**SH**	18	1	10		14	1	14
	HT	15	2	12		10	0	19
	USC	10	3	16		10	2	17
Kinetics	**SH**	1	0	2		2	0	1
	HT	2	0	1		0	0	3
	USC	0	1	2		0	1	2
Performance	**Hop Height**	0	0	1		0	0	1
	Total	82	35	115		53	78	101

%CV ratio of >1.15 is substantially greater variability, 0.87-1.15 is trivial variability, <0.87 is substantially less variability as reported by Drinkwater et al. (2008)

A breakdown by each group of variables for each group

Group	**Control**			**Intervention**		
Variable	**Greater**	**Less**	**Trivial**	**Greater**	**Less**	**Trivial**
EMG	36	28	71	17	74	44
Kinematics	43	6	38	34	3	50
Kinetics	3	1	5	2	1	6
Performance	0	0	1	0	0	1
Total	**82**	**35**	**115**	**53**	**78**	**101**

Summary of all variables in each category and the percentage for each group

	All					
Total	**Greater (N)**	**Less (N)**	**Trivial (N)**	**Greater %**	**Less %**	**Trivial %**
Control	82	35	115	35.3	15.1	49.6
Intervention	53	78	101	22.8	33.6	43.6

*%CV ratio

A summary of quantity of %CV for each group of variables (at pre, post and the change) for each group

Summary		**Group**							
		CON				**INT**			
Variable		**Pre (%CV)**	**Post (%CV)**	**Change (%CV)**	**%CV ratio**	**Pre (%CV)**	**Post (%CV)**	**Change (%CV)**	**%CV ratio**
EMG	**SH**	21.52	18.80	-2.72	0.87	24.36	6.04	-18.32	0.25
	HT	5.15	6.00	20.85	1.16	15.52	9.66	-5.87	0.62
	USC	9.52	13.67	4.15	1.44	21.02	12.93	-8.10	0.61
	Mean	12.06	12.82	7.43	1.16	20.30	9.54	-10.76	0.49
Kinematic	**SH**	39.59	58.50	18.91	1.48	88.53	14.36	-74.17	0.16
	HT	41.83	48.21	6.38	1.15	51.09	52.52	1.43	1.03
	USC	-58.98	-66.23	-17.58	1.12	13.36	5.01	-8.34	0.38
	Mean	7.48	13.49	2.57	0.95	50.99	23.97	-27.03	0.52
Kinetics	**SH**	15.67	14.83	-0.83	0.95	10.27	14.90	4.63	1.45
	HT	13.43	16.03	2.60	1.19	16.27	12.03	-4.23	0.74
	USC	27.93	20.03	-7.90	0.72	27.00	23.60	-3.40	0.87
	Mean	19.01	16.97	-2.04	0.95	17.84	16.84	-1.00	1.02

Global mean – CON = 1.12; INT = 0.68