INFLUENCE OF ATHLETIC TRAINING ON FUNCTIONAL LOWER-EXTREMITY STIFFNESS

Submitted by

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STATEMENT OF SOURCES

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PREFACE

This thesis was prepared to fulfil the criteria for Doctor of Philosophy and is in the format of published and submitted manuscripts and manuscripts prepared for submission. It adheres to the guidelines outlined in "Guidelines on the Preparation and Presentation of a Research or Professional Doctoral Thesis for Examination – Australia Catholic University". The subject matter of the manuscripts presented in this thesis are closely related and form a cohesive and consistent research narrative.

To address the research questions, four journal articles have been prepared and submitted for publication, one of which has been accepted, while another is currently under review. This thesis begins with an ***Introduction*** which provides an overview of the topic area and presents the specific aims, hypothesis, significance and limitations of this body of work. The ***Literature Review*** presents the existing knowledge in the area of stiffness, including stiffness assessment methods, influence of athletic training on stiffness, relevance of stiffness in high performance sport, stiffness and performance and stiffness and injury. Further, the ***Systematic Review*** critically reviews literature pertaining to populations that have been assessed, tasks that been utilised to evaluate stiffness and the assessment of the underlying mechanisms which contribute to stiffness. ***Extended Methodology*** provides an overview of the general methodological elements related to the overall research project. The content of the research studies is presented in ***Chapters 5-8*** in a logical order to address the four specific research questions. The specific details of individual methodology relevant to each research question and results are outlined in each corresponding chapter. The ***Discussion*** chapter summarises the collective results of the four specific papers in relation to the body of works aims and hypothesis and highlights the strengths and limitations of this body of work. Finally, general conclusions are made and suggestions for future research are given.

ABSTRACT

Stiffness of the leg spring quantifies the relationship between the amount of leg flexion and the external load to which limbs are subjected. Lower limb stiffness is essential to facilitate athlete performance and injury risk minimisation. However, stiffness modulation is reliant upon the task requirements, the individual's training status and the athletic training background of individuals. A systematic review highlighted a need to develop an understanding of how differing female athletic populations optimise stiffness to meet task demands and identify appropriate monitoring tools for athlete screening and subsequent longitudinal tracking of leg stiffness changes including potential associations with increased injury risk. Four studies were undertaken; 1) to investigate leg stiffness, joint stiffness and modulation strategy differences in female sub-populations from varied training backgrounds during discrete jumping tasks, 2) to evaluate the differences in leg stiffness between female sub-populations from varied training backgrounds during dynamic jumping and sports-specific tasks and to compare the observed stiffness measures between the tasks, 3) to assess differences in leg and joint stiffness in varying athletic populations during functional tasks and investigate the kinematic and kinetic mechanisms athletes utilise to modulate stiffness to meet sports-specific task demands, and 4) to evaluate longitudinal changes in stiffness across a season of training during dynamic and sports-specific tasks and evaluate potential links to injury risk in athletes. It was hypothesised that stiffness and the contributory kinetic and kinematic modulation strategies athletes utilise would differ between sub-populations. It was also theorised dynamic reactive jumping tasks may provide an adequate relationship to sports-specific tests. Additionally, it was expected that longitudinal changes in stiffness would be evident within the assessed athletic populations. Forty-seven female participants (20 nationally identified netballers, 13 high level endurance athletes and 14 age and gender matched controls) completed six unilateral tasks grouped into two categories; 1) discrete jumping tasks, traditionally utilised to assess stiffness (countermovement jump, drop jump, horizontal jump) and 2) functional sports-specific tasks (sprint, anticipated sidestep change of direction and repetitive hopping). Data was captured using a 10 camera motion analysis system (500 Hz) and force plate (1000 Hz) at three training phases; pre, post and off-season. Participants' self-reported lower body non-contact sports related injury incidence. Statistical analysis evaluated leg stiffness, joint stiffness, contributory kinematic mechanisms and prospective injury risk. No significant differences were evident in leg stiffness measures (p=0.321-0.849) during the discrete jumping tasks despite variations in the underlying contributory mechanisms (p<0.001-0.05). Significant differences were observed in leg stiffness, joint stiffness and the contributing mechanisms across all groups during dynamic and sports-specific tests (p<0.000-0.017). Furthermore, results indicated the control group displayed no stiffness relationship among the sports-specific tasks, while the stiffness relationships evident between tasks within athletic populations reflected athlete training and competition demands. Pre-season results suggested repetitive hopping may serve as an intermediate monitoring tool in athletic populations. However, longitudinally it appeared differences were evident across the season in athletic populations during sports-specific tasks (p=0.005-0.042) which repetitive hopping was unable to identify. Variations in leg stiffness were also evident between the uninjured, soft tissues injury and overuse injury groups (p<0.001-0.039). Furthermore, results of the injury risk prediction model indicated tasks relevant to an athlete's training background predicted soft tissue and overuse injury risk within netball and endurance athletes. It would appear that leg stiffness assessment during basic maximal jumping tasks lack adequate sensitivity to identify clear modulation differences between groups with varying habitual training backgrounds. Differences in the ways groups optimise leg stiffness suggests that functional sports-specific tasks may be superior screening tools to discriminate stiffness differences between groups and as a monitoring tool to assess athletes. These findings highlight the need for practitioners to consider the appropriateness of the task utilised in leg stiffness screening. Results indicated that athletic training influences stiffness modulation strategies. Understanding the differences in the kinematic and kinetic stiffness modulation strategies athletes

utilise to meet training and competition demands may provide insight into potential injury risk. Chronic athletic training appears to influence how athletes optimise stiffness across a season to meet performance demands and is related to injury risk. It appears functional sports-specific tasks are able to accurately identify and monitor longitudinal stiffness changes in athletes.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1. Introduction

Athletic training is known to influence kinematic and kinetic strategies athletes utilise to meet performance demands through the development of the musculoskeletal system, neuromuscular control, co-contraction and regulation of muscle activity (Ambegaonkar et al., 2011; Kuitunen, Avela, Kyrolainen, Nicol, & Komi, 2002; Kuitunen, Kyrolainen, Avela, & Komi, 2007; Kuitunen, Ogiso, & Komi, 2011). Chronic athletic training in high performance sport may place athletes at an elevated risk of injury due to high mechanical loading demands. In high performance sport and applied sports research it is essential to identify tools which allow for early identification of at risk athletes. Lower-extremity stiffness quantifies an athlete's ability to attenuate force during ground contact to achieve optimal performance and is increasingly recognised as a valuable measure of injury risk.

Stiffness of the lower limb describes the relationship between the amount of leg flexion and the external load subjected to the limb (Brughelli & Cronin, 2008a, 2008b). This allows for a complex system of joints, muscles and tendons of the lower limb to be modelled as a simple linear spring. Optimisation of leg stiffness can assist a joint or limb to resist change under an applied load, allowing for the enhanced storage and return of elastic energy necessary for peak performance (Butler, Crowell, & McClay Davis, 2003). Links have been established between stiffness of the lower limb, performance enhancement and injury risk (Ambegaonkar et al., 2011; Comyns, Harrison, Hennessy, & Jensen, 2007; Hobara, Inoue, et al., 2010; Hobara, Kimura, et al., 2010; Laffaye, Bardy, & Durey, 2005; Watsford et al., 2010). Increased lower-extremity stiffness has been linked to stride frequency, running velocity and running economy (Arampatzis, Brüggemann, & Metzler, 1999; Dutto & Smith, 2002; McMahon & Cheng, 1990). However, this may place athletes at an increased risk of injury as higher levels of stiffness have also been associated with overuse injury, while lower levels of stiffness may result in athletes being susceptible to soft-tissue injuries (Butler et al., 2003). It is theorised that an optimal range of stiffness may exist where athletes can benefit from enhanced performance whilst minimising their risk of injury (Butler et al., 2003). Assessment of lower-extremity stiffness can provide practitioners and coaches with a simple representation of a complex musculoskeletal system for injury prevention.

Athletic training influences an individual's ability to effectively modulate stiffness through muscular, physiological and neural adaptations to specific movements and conditions. Research has focused on the cross-sectional profiling of lower-extremity stiffness during basic jumping tasks in recreational and power populations (Arampatzis, Stafilidis, Morey-Klapsing, & Brüggemann, 2004; Boullosa, Tuimil, Alegre, Iglesias, & Lusquiños, 2011; Harrison, Keane, & Coglan, 2004). However, profiling functional lower-extremity stiffness and the associated control strategies utilised by athletic populations from varied training backgrounds during sports-specific tasks appears unclear. Additionally, questions remain as to whether discrete basic jumping tasks, traditionally utilised to monitor stiffness, accurately represent an athlete's stiffness characteristics during training and competition. Accordingly, there is a need to gain insight into appropriate monitoring tools to track performance and identify injury risk in high level athletes.

The main objective of this thesis was to investigate the impact of high level athletic training on lower-extremity stiffness; the associated modulation strategies athletes utilise to meet performance demands; and to evaluate longitudinal stiffness changes and their potential links with increased injury risk in athletic populations. This body of research was designed as four stand-alone studies to address each of the specific aims listed below.

1.1 Aims

The body of work aimed to assess the influence of athletic training on functional lower-extremity stiffness. In order to answer the research questions, the following four specific aims were proposed:

1- To investigate the differences in leg and joint stiffness between athletes from varied training backgrounds during discrete jumping tasks traditionally utilised to assess stiffness. Further, to evaluate the kinematic and kinetic mechanisms athletic populations utilise to modulate stiffness.

2- To investigate differences in leg stiffness and performance variables between athletes from varied training backgrounds during dynamic and sports-specific tasks. Additionally, to evaluate the relationship between stiffness during dynamic jumping and sports-specific tasks.

3- To evaluate differences in leg and joint stiffness in varying female athletic sub-populations and subsequent kinematic and kinetic mechanisms athletic populations utilise to modulate stiffness to meet sports-specific task demands.

4- To assess the longitudinal changes in leg stiffness across a season of training in female athletic sub-populations and the associated injury risk during dynamic and sports-specific tasks.

1.2 Hypotheses

In line with the thesis aims the following hypotheses were proposed:

1- During discrete jump tasks leg stiffness, joint stiffness and the contributory mechanisms would be different between sub-populations as a result of the varied training and conditioning backgrounds of athletes,

2- During dynamic reactive jump tasks and sports-specific tests leg stiffness and its components would differ between sub-populations as a result of varied training and conditioning backgrounds. It was also theorized that dynamic reactive jumping tasks may provide an adequate relationship to sports-specific tests,

3- Stiffness modulation mechanisms including joint stiffness would vary between the investigated sub-populations during dynamic reactive jump tasks and sports-specific tests as a result of their varied training and conditioning backgrounds, and

4- Leg stiffness would vary across a season of training and stiffness responses would differ between sub-populations as a result of varied training and conditioning backgrounds. It was also theorised that high levels of stiffness would be linked to overuse injuries and lower levels of stiffness would be associated with soft tissue injuries. Finally, it was hypothesised that injury risk would vary between sub-populations.

1.3 Significance

Reduction of training days lost to injury is of critical importance in high performance sport to enhance an athlete's preparedness for major competitions. Early identification of 'at risk' athletes is key to early implementation of preventative measures, however the appropriateness of tasks used for detection of injury risk and potential contributing mechanisms remains unknown. Lower-extremity stiffness is a model used to quantify a complex system and provides a simplistic measure for practitioners and coaches to assess improvements in performance and potential injury risk. If the hypotheses of this thesis are accepted, this will advance the knowledge and evidence regarding appropriate monitoring tools for athlete screening. Additionally, it may provide insight into the underlying mechanisms which contribute to injury risk and associated longitudinal changes in stiffness. Identification of appropriate monitoring tools for injury prediction has the potential to provide normative data for detection of at risk athletes. Additionally, it can also enable better assessment and tracking of interventions for stiffness modification. Gaining a clear understanding of the influence of athletic training on lower-extremity stiffness may provide relevant information on ways to optimise performance and minimise injury risk.

1.4 Limitations

The following limitations are acknowledged:

1- Participants were free to complete their normal training and competition activities throughout the duration of the research project. Variability in training hours, load, intensity and competition priorities may have occurred between participants, potentially influencing the results of the research, however it was beyond the control of the researchers.

2- Whilst investigation of high level athletes is a strength of this body of work, this limited the potential number of available, uninjured athletes within athletic populations. As a result, the small sample size of recruited sub-populations may challenge the statistical power of the research.

3- Participant numbers were not evenly distributed across each sub-population which may have increased the power of one particular population and bias results.

4- Although participants were from a similar level of competition, previous training history or experience may have varied amongst individuals. Potentially influencing stiffness properties, kinematic and kinetic control strategies of athletes and associated injury risk.

5- A sufficient sample size from athletes with a pure power background, such as sprinters or track and field jumps athletes was unable to be recruited. This may have potentially limited the thesis's ability to gain a complete understanding of the influence of athletic training on lower-extremity stiffness and limits the relevance of findings to a wider section of sport populations.

6- As data capture was limited to a laboratory setting and required the use of 3D motion analysis, the feasibility of more regular monitoring was outside the scope of the research. Subsequently, isolating the assessment of leg and joint stiffness to specific time points, may limit the ability to gain an understanding of stiffness measures immediately prior to and following injury.

7- Injury treatment and management may influence lower-extremity stiffness measures, however this was outside the control of researchers.

8- Poor participant compliance with weekly training diaries resulted in training load measures being excluded from the research analyses. Thus, only participant training hours were considered as a measure in the present thesis. Training hours is limited in its quantification and understanding of volume, intensity and loading experienced as a result of training and its subsequent effect on stiffness and injury.

9- Whilst care was taken to ensure accuracy of questionnaires used to gather information pertaining to maturation, training hours, training history and self-reported injuries, these measures may be limited by individual's recall accuracy.

10- Laboratory restrictions linked to ground mounted force plates limited the capture of multiple contacts during continuous tasks. As a result, this limited analysis of sports-specific tasks to one contact during the trial.

11- Although assessment of both limbs (dominant versus non-dominant) may provide greater depth of knowledge and relevance to coaches and athletes regarding asymmetry and potential injury risk, this was outside the scope of the research.

12- There is conflicting evidence regarding the impact of the female menstrual cycle on lower-extremity stiffness. It has been suggested the luteal phase (when progesterone is elevated) has a confounding influence of lower-extremity stiffness (Eiling, Bryant, Petersen, Murphy, & Hohmann, 2007). In contrast it has also been suggested that menstrual cycle has no influence of the mechanical properties of the muscle and tendon which aids in the modulation of stiffness (Kubo et al., 2009). Given the mixed literature, logistics and feasibility of tracking each participant's cycle, it was deemed too challenging to control for a participant's menstrual cycle.

13- Lower-extremity stiffness assumes the lower limb is a simple linear spring and does not take into account it is a complex system with many contributory mechanisms.

1.5 Delimitations

The following delimitations were applied:

1- Participants were restricted to females.

2- A strict selection criterion was set in order to reduce variability in data.

3- Participants were aged between 16 to 30 years of age.

4- Participants had to be injury free at the commencement of testing.

5- Participants had to meet full physical maturation guideline to ensure growth and maturation did not influence stiffness measures.

6- Participants from athletic populations were limited to weight bearing sports.

7- Participants were limited to three specific sub-populations; endurance track and field athletes (middle distance and distance athletes), netball and control (general population) participants.
8- Participants from the identified athletic populations were required to meet the qualification standards and selection guidelines outlined for their relevant national championships.
9- Participants of the control populations were to have no competitive or sport specific training history.
10- Testing was isolated to a year training season cycle of athletes (pre-season, post-season and off-season), with testing commencing at pre-season.
11- Leg stiffness assessment was restricted to tasks traditionally utilised to assess stiffness and tasks relevant to an athlete's habitual training background.
12- Joint stiffness and associated kinematic measures were limited to the lower limb i.e. hip, knee and ankle.
13- Reliability of leg stiffness and joint stiffness measures during sport-specific tasks was established.
14- Injuries were limited to those that occurred in the lower limb and were sports related non-contact injuries.

1.6 Definitions

The following definitions apply to the most cited terms presented within this body of work:

Athletic Training: Specific structured activity designed and undertaken to increase proficiency in the chosen sport, may include physical conditioning or technical changes.

Control: Non-active group with no previous specific training background. May engage in sporadic bouts of exercise or lead a sedentary lifestyle. Control participants were to complete no more than 4 hours of physical activity per week.

Contributory Kinematic Mechanisms: Control mechanisms of lower-extremity stiffness modulation which refers to the kinematic and kinetic contribution to joint stiffness and leg stiffness rather than temporal measures such as inter-segmental co-ordinations or centre of mass motion. Includes parameters such as joint displacement, joint moment and touchdown angles at the hip, knee and ankle.

Endurance: Representative of a population who undertakes continuous sustainable exercise, aiming to increase stamina and aerobic endurance. In this research this referred to middle distance and distance athletes from a track and field background.

Elastic Energy: Potential energy that is stored when the body is deformed (spring).

Peak Vertical Ground Reaction Force (PVGRF): The interaction with the force the body exerts on the ground and is measured by a force plate.

High Level: Defined as an athlete who was competing at a national level or above. For netball and endurance athletes this required athletes to meet the qualification standards of guidelines outline for their national championships.

Injury: A physical problem which occurs as a direct result of participation in the athlete's chosen sport, leading to missed or modified consecutive training sessions or competition.

Joint Stiffness (k_{joint}): Describes the stiffness of a single joint described through the ratio of change in joint moment to angular displacement. Joint stiffness measures were isolated to measures at the hip, knee and ankle.

Lower Limb Stiffness/Lower-Extremity Stiffness/Leg Stiffness (k_{leg}): Used to describe the stiffness of the entire leg ideally acting as a single linear spring. It is the ratio of applied force to deformation of the 'spring'. Leg stiffness calculations are implemented to derive stiffness during horizontal movements, mainly used to describe stiffness during running gait.

Netball: Representative of a high intensity intermittent population whose training and competition environment involves intervals consisting of short bouts of all out exercise separated by irregular rest periods. This population regularly performs short sprint efforts, rotational movements about a joint and maximal jumping efforts.

Off-Season: Phase of training marked by a period of ceased or lessening of normal training activity.

Performance Measures: Outcome measures such as peak vertical ground reaction force, centre of mass displacement, contact time, jump height, jump frequency and running velocity.

Pre-Season: Phase of training immediately prior to the start of a new competition season. Athlete undergoes intensive training in preparation for the official competitive season.

Post-Season: Phase of training immediately following the cessation of the end of the official competitive season.

Spring: A mechanical device that deforms under an applied force and return to it's normal state when the force is released. In the context of the present thesis it refers to a simplistic model applied to the lower limb. Whereby the entire limb including, joints, muscles, tendons and contractile elements act in a spring like manner, deforming under applied force relative to the 'stiffness' of the spring.

Sports-Specific: Tasks that are representative of performance demands of an athlete's daily training or competition environment.

Stiffness: Relationship between the deformation of the body and a given force. Stiffness increases the resistance of the muscle to change under an applied load. The use of stiffness in this thesis refers leg stiffness.

Vertical Stiffness (k_{vert}): One form of stiffness, used to describe linear movements of locomotion that occur in a vertical direction i.e. hopping and jumping. It is equal to peak vertical force divided by the maximum vertical displacement. Stiffness determined through leg stiffness formulas for vertical place movements equates to stiffness derived through vertical stiffness calculations. In this thesis for tasks performed in the vertical plane results will be determined through leg stiffness calculations to ensure consistency in methodology across all tasks.

Chapter 2. Literature Review

The concept of stiffness in relation to musculoskeletal health and movement has been investigated (Butler et al., 2003). Key concepts related to stiffness will be discussed in this narrative literature review. The term stiffness has been used to refer to vertical stiffness, leg stiffness, joint stiffness, musculotendinous stiffness, tendon stiffness and passive stiffness of the lower-extremity (Brughelli & Cronin, 2008a; Butler et al., 2003). The focus of this research is the vertical, leg and joint stiffness of the lower extremity during the eccentric phase of ground contact. Therefore, within this research the term “lower-extremity stiffness” or “stiffness” refers to both measures of vertical and leg stiffness of the lower-extremity.

This chapter aims to address the following aspects associated with leg and joint stiffness in relation to athletic training:

1. Definition and discussion of functional lower-extremity stiffness and the associated kinematic and kinetic modulation strategies,
2. Research methods in stiffness, and
3. The relevance of stiffness in high performance sport.

2.1 Stiffness in Human Movement

Lower-extremity stiffness in the context of human movement, refers to the relationship between the compression of the leg spring and the external force applied to this spring. This relationship is quantified by Hooke's Law, which governs the proportionality between the external load and body deformation (Butler et al., 2003). Stiffness values represent a complex system in the human body where stiffness arises from the contribution of muscles, tendons, ligaments, cartilage and bone tissues (Butler et al., 2003; Latash & Zatsiorsky, 1993). Stiffness allows for the neuromuscular system to increase its resistance to muscle length changes under an applied load (Brughelli & Cronin, 2008a). This is of particular interest in maximal effort tasks such as jumping and sprinting as it allows for the rapid transmission and production of forces in a short period of time which is beneficial to performance (Ackland, Elliott, & Bloomfield, 2009).

Conceptualising the lower extremity as a spring model allows lower extremity function to be described as a simple linear spring as the ratio of maximal vertical force to maximal leg spring compression (Butler et al., 2003). This is generally expressed by the following formula (Equation 1):

Equation 1

$$k = \frac{F_{peak}}{\Delta y}$$

Where *k* is used to represent the stiffness coefficient, F_{peak} to represent the maximal vertical force to which the lower limbs are subjected to and Δy the leg spring compression. These specific parameters, leg compression and peak force, occur during the mid-stance phase of ground contact time during running, jumping or hopping (Brughelli & Cronin, 2008a; Butler et al., 2003). Studies investigating lower extremity stiffness are becoming more prevalent in the biomechanics literature (Dutto & Smith, 2002; Farley & Gonzalez, 1996; Hobara, Inoue, et al., 2010; Hobara, Kimura, et al., 2010; Kuitunen et al., 2007; Pruyn et al., 2013; Watsford et al., 2010) as researchers strive to further understand a complex system through a simple model known to have strong links with both performance and injury (Butler et al., 2003; Granata, Padua, & Wilson, 2002; Padua et al., 2006; Pruyn et al., 2012; Pruyn et al., 2013; Watsford et al., 2010).

Stiffness has been defined and hence calculated in a variety of ways depending on the question that has been investigated (Butler et al., 2003). Of these; vertical, leg (McMahon & Cheng, 1990) and joint stiffness (Stefanyshyn & Nigg, 1998) are the most appropriate measures in quantifying stiffness in functional sport-related movements. Vertical stiffness is used to assess hopping and jumping actions as movement occurs in a vertically linear motion, whereas leg stiffness is the preferred parameter in actions such as walking and running where calculations take into account the horizontal and vertical displacement of centre of mass (Brughelli & Cronin, 2008a). Joint stiffness quantifies the stiffness of a singular joint and has been utilised to assess the means by which individuals modulate stiffness to meet task demands.

2.1.1 The Spring Mass Model

Measures of stiffness can be isolated to quantifying stiffness of a single muscle fibre to modelling the entire body as a mass and spring (Butler et al., 2003), where force is required to stretch or compress the spring (Brughelli & Cronin, 2008a). During human locomotion such as running, individual stiffness values of ligaments, tendons, bones and muscles, all of which contribute to mechanical stiffness, can be described through a simple spring-mass model which quantifies the relationship between applied force and deformation of the leg (Brughelli & Cronin, 2008b; Butler et al., 2003; Farley & Gonzalez, 1996). The stiffness of the spring controls the mechanical interaction of the musculoskeletal system and surrounding environment during the ground-contact phase of locomotion (Ferris & Farley, 1997). The spring-mass model is comprised of a single linear spring and a point of mass which is equivalent to the mass of the body. This model can be used to predict the mechanics of running gait, estimate leg stiffness and has also been shown to be linked to performance outcome measures of contact time, vertical velocity, stride length, stride frequency and rate of force development (Dutto & Smith, 2002; McMahon & Cheng, 1990).

Ideally a spring is mass-less and will only move in one direction, whereby the stiffness of the spring is independent of time, length or velocity (Butler et al., 2003). Accurate spring-mass models will account for all contributing mechanisms such as tendons, ligaments, muscles, cartilage and bone and illustrate muscle force changes as a function of contraction velocity (Butler et al., 2003). The model should also take into account the viscosity, time delays of the muscle reflex, central nervous system control that is required and describe independent displacements that occur at the joints. Multiple series and parallel elastic components that are controlled by more than two muscles and bi-articular muscles should also be considered (Butler et al., 2003; Latash & Zatsiorsky, 1993).

It is believed that springs e.g. the leg; that are compressed will obey Hooke's law ($F = kx$; where F = restoring force exerted by the moment, k = spring constant, x = displacement of the end of the spring from its equilibrium position) where force production of a spring is proportional to the displacement from its equilibrium length (Brughelli & Cronin, 2008a, 2008b). According to Hooke's Law, stiffness acts as an ideal spring, whereby the leg is often used to represent the spring needed to support the entire body (Brughelli & Cronin, 2008a; Butler et al., 2003). When the spring (stiffness in the leg), is stretched or compressed during the eccentric phase of the movement, the muscle stores and returns elastic energy (Brughelli & Cronin, 2008a; Butler et al., 2003; Farley & Gonzalez, 1996). It has been shown that greater levels of stiffness in the spring result in improved performance, exhibited through greater running velocities and reduced contact time, and helps to resist the collapse of the lower body during the landing phase by stabilising the joint, thus decreasing the risk of injury (Ackland et al., 2009; Brughelli & Cronin, 2008a; Toumi, Best, Martin, & Poumarat, 2004).

The lower limb is often described in stiffness literature as a spring, loaded by the body weight and inertia of the individual's body mass (McMahon & Cheng, 1990; Morin, Dalleau, Kyröläinen, Jeannin, & Belli, 2005; Morin, Jeannin, Chevallier, & Belli, 2006). This paradigm is effective in describing and investigating the storage and utilisation of elastic energy within the lower limbs. During locomotion musculotendinous structures in the leg alternately store and return elastic energy during the contact phase of movement, known as the stretch shortening cycle (Morin et al., 2006).

The first known spring-mass model of the lower extremities was formulated by McMahon and Cheng (1990). The model was formulated to investigate the interaction and subsequent relationship between various mechanical parameters during hopping and running. The study established that i) during the mid-stance phase of movement the centre of mass was lowest during running and highest during walking and ii) suggested energy was able to be stored in an elastic form within stretched tendons, muscles and possibly bent bones. The model suggested that the leg could act as a linear spring where the body mass compresses the spring with a downward vertical velocity which is reversed during the propulsion phase. It was ascertained that the stiffer the spring, the shorter the contact time and the higher the peak vertical ground reaction force. Thus it was suggested that leg stiffness provides a resistance to the deformation of the body during impact, thus improving performance.

2.2 Functional Measures of Stiffness

Lower extremity stiffness can be grouped into two categories: functional and clinical measures of stiffness (***Figure** 2.1*). Clinical measures are beneficial in providing detailed information regarding the underlying tissue and tendon stiffness properties, these measures include tendon stiffness (Kubo, Kawakami, & Fukunaga, 1999), muscle-tendon stiffness (Wilson, Wood, & Elliott, 1991), musculoarticular stiffness (Ditroilo, Watsford, Murphy, & De Vito, 2011) and passive stiffness (Reid & McNair, 2004). Although clinical measures evaluate stiffness at a micro-level they are isolated to measurement through oscillation systems, ultrasonography and isokinetic devices, and as a result are limited in their functional application to sport. Functional measures of stiffness are advantageous in their ability to quantify stiffness during tasks relevant to sport, these measures include vertical stiffness

(McMahon & Cheng, 1990), leg stiffness (McMahon & Cheng, 1990) and joint stiffness (Stefanyshyn & Nigg, 1998). Due to the practical sporting relevance of functional measures of stiffness, this thesis will focus on these methods of quantifying lower extremity stiffness.

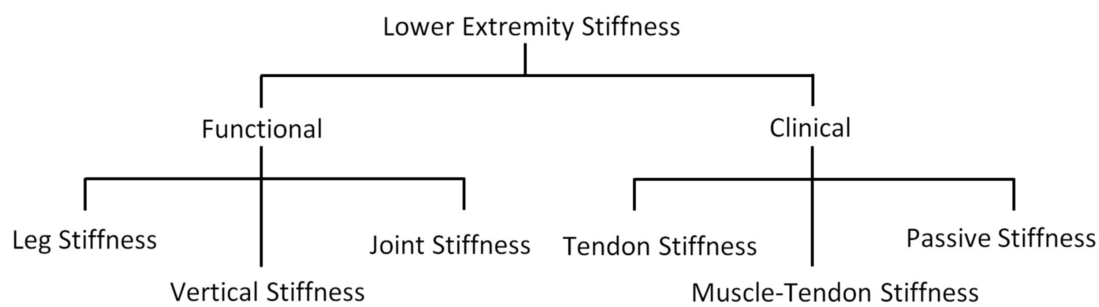

Figure 2.1 - Breakdown of lower extremity stiffness measures.

Research models stiffness of the lower limb as a linear spring, whereby the force displacement curve can be utilised to assess performance of human hopping or running in a simplistic way (Brughelli & Cronin, 2008b; Butler et al., 2003). While in reality the curve may deviate from a strictly linear relationship, in stiffness calculations, the model assumes that the spring is linear where ground reaction force traces can be plotted against the downward slope of the vertical centre of mass displacement. Whereby, the resultant curve equates to two linear lines which mirror each other representing the touchdown and toe-off phases of contact (Brughelli & Cronin, 2008b) As the slope of the two lines increases, in accordance with the theoretical model stiffness also increases. Recent research suggests high level sprinters may deviate from the classic spring mass model at high running velocities, however non-sprint athletes across a range of running velocities including maximum velocity displayed spring like behaviour. Thus the spring mass model appears appropriate for non-sprint athletes (Clark & Weyand, 2014)

2.2.1 Vertical Stiffness

Vertical stiffness describes movement that occurs in a vertical direction such as hopping and jumping (Butler et al., 2003). The assessment of vertical stiffness models the vertical motion of the centre of mass during the contact phase (initial contact to mid-stance) of movement (Morin et al., 2005; Morin et al., 2006). It is defined as the ratio of maximal force to the maximal vertical displacement of the centre of mass at its lowest point, usually during the mid-stance phase of movement (Morin et al., 2005); (Figure 2.2). Vertical stiffness can be modulated through joint kinematics and a neuromuscular recruitment plan which is portrayed by the corresponding muscle activation patterns adopted during movement execution (Ackland, et al., 2009).

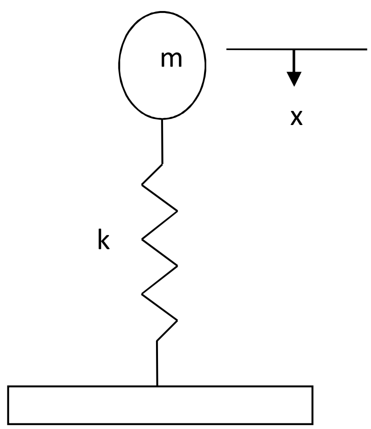

Figure 2.2- Ideal spring mass model used to determine vertical stiffness. Orientation of the leg must be vertical. (Adapted from Butler et al., 2003).

Vertical stiffness has been found to increase with running velocity and hopping height (Brughelli & Cronin, 2008b). Increased vertical stiffness is believed to aid in performance, by assisting the lower extremity joints to resist the collapse during the landing phase of movement (Butler et al., 2003), suggesting the rate of force production and energy transfer during the concentric phase of movement (push-off) is enhanced. This is beneficial as it allows for optimal performance and reduced risk of injury, as contact time is decreased and increased joint stability can be achieved (Brughelli & Cronin, 2008b).

Increasing vertical stiffness facilitates the ability of the spring-mass system to recoil quicker (Butler et al., 2003). This has been shown to be beneficial for individuals as it allows for a rapid absorption of force and elastic energy, generation of power and kinetic energy during the ground contact phase of the movement from foot strike to toe off (Ackland et al., 2009; Brughelli & Cronin, 2008a; Butler et al., 2003). Higher vertical leg spring stiffness levels can be achieved by increasing muscular pre-activation prior to contact (Butler et al., 2003).

Vertical stiffness occurs as a result of the interaction of peak vertical forces and vertical centre of mass displacement. Thus, constant vertical stiffness is able be determined by solving k in the equation $F = ks$ (where F= ground reaction force after allowing for body weight, k= vertical stiffness and s= vertical displacement of the centre of mass). Given that vertical stiffness has a direct dependence on peak vertical ground reaction force and an inverse relationship to vertical displacement of the centre of mass, it would be expected that increases in peak vertical force would result in increases in vertical stiffness along with velocity, however this is not the case. Ground reaction force does not increase at the same rate as vertical stiffness, due to centre of mass displacement decreasing with velocity increases (Brughelli & Cronin, 2008a, 2008b; Butler et al., 2003). It is important to note that leg stiffness equates to vertical stiffness measures during movements in the vertical plane and, as a result the terms leg stiffness and vertical stiffness have been used interchangeably.

2.2.2 Leg Stiffness

Leg stiffness refers to the stiffness of the entire leg as it acts like a single linear spring and accounts for an individual's horizontal velocity, contact time, resting leg length and peak vertical ground reaction force (Butler et al., 2003). Similar to vertical stiffness, peak vertical force and maximum displacement of the leg spring occurs during the mid-stance phase of movement.

Compression of the leg spring during locomotion is ascertained from the individual's maximal vertical displacement of the centre of mass, length of the leg spring at ground contact and the angle of the leg landing (Θ) (Brughelli & Cronin, 2008a, 2008b). Thus leg spring compression can be described as the relationship between the foot landing and centre of mass (Figure 2.3).

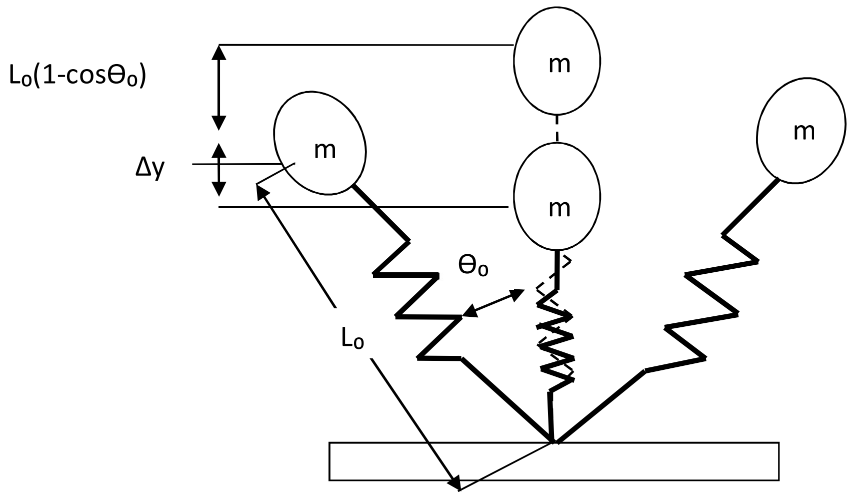

Figure 2.3- Leg stiffness model which demonstrates centre of mass displacement and change in leg length during mid stance phase. Where m= mass, L= leg spring length, Θ= leg landing angle and y= vertical displacement of the centre of mass. (Adapted from Butler et al., 2003).

During horizontal tasks such as running, the foot strikes the ground at a point where the centre of mass is not always directly over the foot. As a result, it forms a leg landing angle referred to as theta Θ (Figure 2.2). An interesting observation of this model establishes that if the mass of the model was to move in a purely vertical motion then the leg landing angle becomes 0 and as a result $L_0(1 - \cos \Theta)$ also becomes equal to zero. Consequently, leg stiffness then becomes equal to vertical stiffness during vertical movement (Hobara, Inoue, et al., 2010; Morin et al., 2006). Research has demonstrated that during slow to moderate horizontal running velocities (~5.0 m/s) leg stiffness remains constant in non-athletic populations (Farley, Glasheen, & McMahon, 1993; He, Kram, & McMahon, 1991; Morin et al., 2005). This occurs as leg stiffness does not increase at the same rate as maximal vertical force, thus an increase leg spring length occurs. Additionally, it has been shown athletes displayed spring like behaviour at velocities ranging from 3.0 – 8.1 m/s (Clark & Weyand, 2014).

2.2.3 Joint Stiffness

Stiffness calculations have also been extended to modelling stiffness of a single joint (hip, knee or ankle) as a rotational spring to provide insight into joint contributions to stiffness of the leg spring (Butler et al., 2003). Joint stiffness is determined through the ratio of change in joint moment to angular joint displacement in the sagittal plane. Stiffness of the joint is dependent on a multitude of factors such as muscle activation, joint angle, range of motion and the joint velocity during ground contact (Brughelli & Cronin, 2008b). Joint stiffness has been suggested to contribute to the work done by the muscles leading to optimisation of centre of mass velocity aiding in potential performance enhancements (Kuitunen, Komi, & Kyrolainen, 2002).

Few studies have evaluated joint stiffness contributions to movement or how athletes modulate stiffness to meet performance demands. Of the limited studies investigating joint stiffness of athletes during running, research has suggested that running velocity increases as a result of increased stiffness on a knee joint. As a result, it is believed that this joint plays a critical role in the modulation of stiffness during running of recreational runners (Arampatzis et al., 1999; Kuitunen, Komi, et al., 2002). In contrast, for track and field athletes, it is speculated the hip joint plays an important role in increased running velocity through increased output of hip extensor muscles (Kuitunen, Komi, et al., 2002; O'Meara & Moresi, 2012; Williams, 2000). More effective hip extensor activation can assist in reduced flexion down the kinematic chain allowing for reduced ground contact time and improved mechanical efficiency resulting in improved running economy (Williams, 2000). Additionally, during hopping, ankle stiffness appears to be the main contributor in modulating stiffness of the leg spring (Farley & Morgenroth, 1999; Hobara, Kimura, et al., 2010). However the understanding of the mechanical control and joint contributions to stiffness modulation is relatively unknown amongst athletic populations, particularly during sport specific tasks which involves the co-ordination of multiple joints.

2.2.4 Underlying Mechanisms in Stiffness Modulation

An advantage of assessing lower limb stiffness is the simplistic representation of the mechanical behaviour of the musculoskeletal system. However, this may disregard the mechanism contributions of a multi-joint spring which comprises of various elastic, neural and tendinous properties (Latash & Zatsiorsky, 1993). The ability to optimise leg and joint stiffness is dependent upon the muscles capacity to produce force and the rate at which force is produced (Butler et al., 2003). Stiffness control of the leg spring and joint is known to be dependent upon the co-contraction of agonist and antagonist muscles, muscle pre-activation and neuromuscular regulation (Butler et al., 2003).

Activation frequency of the muscle via electrical pulses affects the generation and maintenance of force (Binder-Macleod, Lee, Fritz, & Kucharski, 1998). In order to produce maximum force and hence facilitate joint stiffness, muscles must be maximally active. The opposite effect occurs if the muscle remains unstimulated i.e. smaller forces are produced and as a result lower levels of stiffness are generated as the muscles ability to accommodate for performance demands is reduced (Grabiner, 1993). Neuromuscular adaptations play an important role in optimal muscle activation in line with adjustments the body makes in regard to mechanical joint behaviour and structural modifications in muscle tendon units (Nicol, Avela, & Komi, 2006a).

Neural adaptations to training and conditioning influence the overall activity of a muscle (Nicol et al., 2006a) and aids in the regulation of stiffness. In order to successfully regulate stiffness, the central nervous system (CNS) requires both force feedback and muscle length feedback to constantly update muscle function. This is done via muscle spindles which relay information from the CNS, to accommodate for load and length changes (Enoka, 2002). When neural input from CNS decreases, for example during fatigued conditions, the muscles' ability to accommodate for these changes also diminishes (Nicol et al., 2006a).

Motor unit activation rates, modulated by the CNS, that allow muscle force optimisation during sustained frequent muscle contractions have been defined as 'muscle wisdom' (Binder-Macleod et al., 1998). Training has the ability to develop this 'muscle wisdom' whereby force is produced in a feed forward fashion, by muscle pre-activation, to produce optimal performance (Grabiner, 1993).

During prolonged sub-maximal running, high levels of neuromuscular activity are required to respond to continually changing environmental and physiological conditions by providing continued neural input. As the timing of muscle contraction can be regulated through peripheral and central neural inputs it is plausible that these same inputs can influence leg kinematics. Increases in the degree of knee flexion have been shown to be correlated with decreased leg stiffness (McMahon, Valiant, & Frederick, 1987). Leg kinematics therefore can modify stiffness.

Enhanced storage and return of elastic energy is necessary for optimal performance and has been shown to be dependent on a high level of muscle activation (Winter, 2005). Given that stiffness also depends on high levels of muscle activation it can be inferred that increases in stiffness leads to increased muscle elastic energy storage, more specifically during the eccentric phase of the stretch shortening cycle (Butler et al., 2003). This allows for potential elastic energy to be utilised during subsequent concentric phases where the muscle is lengthened (Avela & Komi, 1998) resulting in improved performance particularly in events where maximal force outputs are required such as jumping and sprinting (Ackland et al., 2009). Due to more effective storage and utilization of elastic energy lower energy costs are associated with high leg stiffness generation (Kuitunen et al., 2007).

During the ground contact phase in running for instance, as the foot strikes the ground and remains planted, the runner's centre of mass continues to move in the direction of the movement, causing the knee joint to move in a posterior-anterior fashion. This causes the ankle joint to dorsi-flex, whereby plantar flexors muscles are stretched, thus allowing elastic energy to be stored (Ackland et al., 2009). The stored elastic energy then assists the concentric contractions of plantar flexors, thus resulting in rapid plantar flexion of the foot during the toe-off phase of movement. Athletic training is known to influence key kinematic and kinetic strategies, however there is a need to investigate the training influence on joint level contributions such as angular displacement, joint moments, joint touchdown angles and force production.

Functional measures of stiffness allow for the quantification of a complex system of joints, muscles and tendons of the lower limb by modelling it as a simple linear spring. It appears lower-extremity stiffness is modified by joint stiffness through kinematic and kinetic adjustments. Researchers have quantified leg and joint stiffness measures through varies techniques and technology.

2.3 Research Methods in Stiffness

2.3.1 Equipment

Various pieces of equipment have been utilised to quantify and evaluate stiffness. As stiffness is computed as the ratio of peak force to centre of mass displacement, force plates, film/video, kinematic arms, contact mats and pressure sensors are the instrumentation favoured by most researchers to measure vertical stiffness, leg stiffness and joint stiffness during locomotion (Brughelli & Cronin, 2008a). Each piece of equipment has its own strengths and weaknesses in determining stiffness which are outlined below (Table 2.1).

2.3.1.1 Force Gauges

2.3.1.1.1 Force Plates

Force plates are used extensively (Hobara, Kimura, et al., 2010; Horita, Komi, Hämäläinen, & Avela, 2003; Kuitunen et al., 2007; Morin et al., 2006; Padua et al., 2006) in determining leg and vertical stiffness as they provide a direct measure of ground reaction forces during the contact phase of movement. Vertical centre of mass displacement can be determined through the double integration of vertical ground reaction force data (Cavagna, 1975). Combining this measure with the peak ground reaction force during mid stance allows vertical stiffness to be calculated during hopping and running movements. Although force plates are effective in determining vertical and leg stiffness, they are expensive pieces of equipment that are difficult to transport. Ground mounted force plates also limit the number of steps which can be evaluated (Brughelli & Cronin, 2008a). As a result, researchers have investigated additional forms equipment such as contact mats, pressure sensors, kinematic arms and video to derive surrogate measures of ground reaction force and centre of mass displacement.

2.3.1.1.2 Contact Mats

Contact mats and pressure sensors provide a simplistic means of determining vertical and leg stiffness. These particular forms of equipment are easily accessible to industry professionals, easy to use and feasible due to their inexpensive nature when compared to other forms of equipment such as force plates. Single contact mats allow vertical stiffness to be estimated during hopping and running movements determined from contact time, aerial time and body mass where it is assumed centre of mass displacement displays sine wave characteristics (Dalleau, Belli, Viale, Lacour, & Bourdin, 2004). Leg stiffness assessed during running activities through the implementation of pressure sensors that determine the mechanical parameters of contact and aerial time. A radar gun is also utilised in order to measure velocity, thus allowing stiffness to be ascertained (Brughelli & Cronin, 2008a).

2.3.1.1.3 Other Device

Kinematic arms consist of four rigid bars linked together by three joints and allow researchers to measure the displacement of the centre of mass during movement in all three planes of motion (Belli, Lacour, Komi, Candau, & Denis, 1995). The distal end of the kinematic arm is attached to the participant whilst they undertake activities such as running and walking on a treadmill, while the proximal end is connected to a reference point, thus enabling the kinematic arm to move freely through all three planes. By calculating the angle between the given bar lengths through the use of electrical potentiometers the immediate position of the distal end relative to the proximal end can be ascertained, allowing researchers to establish body displacement in all three planes of movement (Brughelli & Cronin, 2008a).

2.3.1.2 Video

Motion capture, both 2 dimensional and 3 dimensional, allows for displacements, joint positions, velocities and accelerations to be obtained. When combined with force plate analysis it enables the calculation of joint moments by inverse dynamic methods (Winter, 2005) and consequently joint stiffness during movement. In order to ascertain joint displacement, required for determining stiffness, digitising of the defined joint centres during the specified movement is required.

Video data obtained through high-speed cameras allows for the quantifying of human movement in a biomechanics setting. Through the use of reflective markers; which provide shape, contrast and colour; the camera is able to be used as a semiautomatic data analysis system. The shape of the markers provides an identifying mechanism used to pinpoint anatomical landmarks. Video data is effective in providing kinematic analysis of movements and allows researchers to determine displacements, accelerations and velocities of segments (Nigg & Herzog, 2007; Winter, 2005).

Table 2.1- *Summary of Available Equipment Used to Quantify Stiffness in Research.*

Equipment	Advantages	Disadvantages
Force Plate Only	• Direct measure of GRF • Double integration GRF provides COM • Can determine vertical • Used in vast amount of literature	• Expensive • Difficult to transport • Limited in the number of steps that can be taken
Force Plate and Motion Analysis	• Records displacement, velocities and accelerations of joint during movement • Can derive leg and joint stiffness	• Digitising is a time consuming process • Inaccurate estimations of COM can occur if marker placements are inaccurate • Capturing speeds of camera during high speed movements
Force Plate and Kinematic Arms	• Direct measure of GRF • Measure displacements of COM through all three planes of movement	• Limited to movements on a treadmill
Contact Mats and Pressure Centres	• Simple to use, easily accessible to industry professionals • Feasible compared to other more expensive forms of equipment e.g. force plate	• Numerous mechanical parameters need to be obtained in order to derive stiffness • Derived force and displacement measures are assumed

2.3.2 Methods of Calculating Vertical Stiffness

To date four methods have been employed to calculate vertical stiffness (Brughelli & Cronin, 2008b; Butler et al., 2003) (Table 2.2).

1- The method proposed by McMahon and Cheng (1990) (equation 2) is the most commonly used protocol. It is dependent upon the two mechanical parameters of maximum vertical force and maximum vertical displacement of the centre of mass. It is assumed that peak vertical ground reaction force is achieved and the centre of mass reaches maximal displacement during the mid-stance phase of movement. The equation states vertical stiffness is equal to the peak vertical force divided by maximal vertical displacement of the centre of mass. This method of quantifying vertical stiffness has predominantly been associated in the analysis of determining stiffness from force plate only data, although motion analysis can be utilised to determine centre of mass displacement.

Equation 2-

$$K_{vert} = \frac{F_{max}}{\Delta y}$$

The advantage of this method is that it allows for a variety of body sizes and animals to be compared on an equal level.

2- The methodology of McMahon et al (1987) (equation 3) requires a force plate in order to calculate vertical stiffness. The formula states vertical stiffness (K_{vert}) is equal to mass multiplied by the square of natural frequency of oscillation.

Equation 3-

$$K_{vert} = m\omega^2$$

The natural frequency of oscillation (ω) is determined from contact time (F/t curve) and vertical velocity (single integration). Since this particular study no other researchers have implemented this particular method to calculate vertical stiffness during jumping and running activities (Brughelli & Cronin, 2008b; Butler et al., 2003).

3- The method proposed by Cavagna et al (1988) (equation 4) implements the use of a force plate in order to determine vertical stiffness. It is essentially the same formula used in the McMahon et al (1987) study, the only difference between the two calculations is the means used to calculate the natural frequency of oscillation (ω). The force time curve ascertains effective contact time during the stance phase of movement i.e. that amount of time where the vertical force is greater than body weight (P/2), where P= period of oscillation. From this the natural frequency of oscillation (ω) can be determined (equation 4).

Equation 4-

$$\left(\omega = \frac{2\pi}{P}\right)$$

The formula $K_{vert} = m\omega^2$ is then implemented in order to calculate vertical stiffness. Only three other studies to date have implemented this formula to calculate vertical stiffness (Cavagna, 2006; Cavagna, Heglund, & Willems, 2005; Divert, Baur, Mornieux, Mayer, & Belli, 2005).

4- Dalleau et al (2004) reported the only known method to date that does not require a force plate in order to determine vertical stiffness. The protocol implemented the use of pressure sensors to determine the essential parameters of contact time, aerial time and body mass, required to calculate vertical stiffness. The calculated vertical stiffness was reportedly modelled through a vertical force sine wave. This was seen to be appropriate as the levels of force in a spring mass model are expected to oscillate in the shape of a sine wave. The equation implemented in the Dalleau et al (2004) study to calculate vertical stiffness is featured below (equation 5):

Equation 5-

$$\frac{K_{vert}}{m} = (\pi(T_v + T_c))/(T_c^2 \left(\left(\left(T_v + \frac{T_C}{\pi}\right)\right) - \left(\frac{T_c}{4}\right)\right))$$

Where:

T_v= Flight time

T_c= Contact time

m = Mass of body

It is clear that these four methods are effective in calculating vertical stiffness during movements such are jumping, hopping and running. However, it can be suggested that these calculations also have associated limitations when determining leg stiffness. These particular equations do not account for the horizontal displacement of the centre of mass due to hip, knee and ankle flexion. As a result, findings using vertical stiffness calculations cannot be applied to running gaits where centre of mass displacement occurs both vertically and horizontally. Thus leg stiffness equations are required to be implemented in order to calculate stiffness of the leg spring when actions occur both in a vertical and horizontal motion.

Table 2.2- *Summary of Vertical Stiffness Calculations (Adapted from Butler et al., 2003).*

	Equation	Reference	How to Measure
1	$K_{vert} = \frac{F_{max}}{\Delta y}$ Where F_{max}= maximum vertical force; Δy = maximum vertical displacement of centre of mass	McMahon and Cheng (1990)	Force plate
2	$K_{vert} = m\omega^2$ Where m = mass of the body; ω =natural frequency of oscillation	McMahon et al (1987)	Force plate
3	$K_{vert} = m\omega^2$ $\omega = \frac{2\pi}{P}$ Where m = mass of the body; ω =natural frequency of oscillation; P = period of oscillation	Cavagna et al (1988)	Force plate
4	$\frac{K_{vert}}{m} = (\pi(T_v + T_c))/(T_c^2\left(\left(\left(T_v + \frac{T_C}{\pi}\right)\right) - \left(\frac{T_c}{4}\right)\right))$ Where T_v= flight time; T_C= contact time; m = mass of body	Dalleau et al (2004)	Pressure Sensors

2.3.3 Methods of Calculating Leg Stiffness

Currently there are three methods in which leg stiffness of the spring can be calculated (Brughelli & Cronin, 2008b; Butler et al., 2003). Below reviews the three methods studies have employed in order to derive leg stiffness during movements such as running (Table 2.3).

1- McMahon and Cheng (1990) (equation $K_{Leg} = \frac{F_{max}}{\Delta L}$) directly measured vertical ground reaction force (F_{max}) from a force plate. Changes in leg spring length (ΔL) were obtained from running velocity, leg landing length, leg length and the vertical displacement of the centre of mass. Leg landing angle was determined from contact time, running velocity and initial leg length. Leg stiffness was then calculated as the ratio of maximum vertical force to the maximum change in leg length established during the mid-stance phase. Vertical force was utilised based on the assumption that peak vertical ground reaction force occurred when the centre of mass reaches its lowest point during mid-stance.

2- Morin et al. (2005) method demonstrated that leg stiffness could be derived from initial leg length (L) and forward velocity in order to determine the changes in leg spring length (Equation 6). Running velocity was ascertained through the use of a radar gun, while initial leg length was established by measuring the length from the greater trochanter to the floor. The equation was validated when stiffness scores were compared to those of McMahon and Cheng (1990), in comparison the scores were found to be less than 0.67% to 6.93% in range of McMahon and Cheng (1990) thus deeming the scores reported via Morin et al. (2005) method to be acceptable. The advantage of this methodology is that pressure sensors are implemented hence expensive pieces of equipment such as force plate and force transducers are not required in order to determine leg stiffness scores.

Equation 6-

$$K_{Leg} = L - (L^2 - \left(\left(\frac{vT_C}{2}\right)\right)^{0.05} + \Delta y$$

Where:

v = Horizontal velocity

T_c= Contact time

Δy= Maximum vertical displacement of the centre of mass during the eccentric phase of contact.

3- Arampatzis et al. (1999) implemented the use of a force plate to ascertain the peak vertical ground reaction force. However, changes in leg length were established through the use of a two segment model (hip to knee, knee to ankle) assessed with a high speed camera (Equation 7). This study however reported higher degrees of leg stiffness values (> 35 kN/m) when compared to other studies (Farley & Gonzalez, 1996; He et al., 1991; McMahon & Cheng, 1990; Morin et al., 2005) which all reported scores (<20 kN/m). These differences could be explained by differing measurements of leg length or underestimation of segment displacements derived from force plate measures (Kibele, 1999).

Equation 7-

$$K_{Leg} = \frac{F_{max}}{\Delta VCL}$$

Where:

ΔVCL = Change is leg length derived from video analysis

Table 2.3- *Summary of Leg stiffness calculations (Adapted from Butler et al., 2003).*

	Equation	Reference	How to Measure
1	$$K_{Leg} = \frac{F_{max}}{\Delta L}$$ Where F_{max} = maximum vertical force; $\Delta L = \Delta y + L(1 - cos\theta)$; $\theta = \sin(\frac{vT_C}{2L})$; Δy= vertical displacement of the centre of mass; v= forward velocity; L= initial leg length	McMahon and Cheng (1990)	Force plate
2	$$K_{Leg} = L - (L^2 - \left(\left(\frac{vT_C}{2}\right)\right)^{0.05} + \Delta y$$ Where L = initial leg length; v = velocity; T_C= contact time; Δy = maximum vertical displacement of centre of mass	Morin et al. (2005)	Pressure sensors
3	$$K_{Leg} = \frac{F_{max}}{\Delta VCL}$$ Where F_{max} = maximum vertical force; ΔVCL = change is leg length derived from video analysis	Arampatzis et al. (1999)	Force plate and high speed video cameras

2.3.4 Methods of Calculating Centre of Mass Displacement

Centre of mass displacements can be calculated through force plate or video data. A variety of techniques have been implemented to estimate centre of mass displacements which is essential to determine displacement of the body during movement (Brughelli & Cronin, 2008b; Butler et al., 2003). However, there are discrepancies amongst the literature regarding the most appropriate method to implement in order to determine centre of mass displacement. As a result, the displacement of the centre of mass can be overestimated or underestimated thus affecting the predicted stiffness score of the lower extremity (Ranavolo et al., 2008).

When determining centre of mass displacement from ground reaction force plate data, the most prevalent method found within the literature is the Cavagna (1975) methodology employed in a range of studies (Divert et al., 2005; Farley & Gonzalez, 1996; Granata et al., 2002; Morin et al., 2005). Cavangna (1975) demonstrated that vertical displacement of the centre of mass could be calculated through the double integration of the vertical acceleration over time (equation 8). Vertical acceleration was obtained from vertical ground reaction force data (N) divided by the body mass (m) of the participant after subtracting the gravitational acceleration (equation 9). However, this method only accounts for the changes that occur to the centre of mass purely in a vertical motion under a given force and does not consider the changes to the centre of mass that may occur in a horizontal plane as the assumption is made that the horizontal force is equal to zero (Zabjek, Coillard, Rivard, & Prince, 2008). This may overestimate or underestimate the centre of mass displacement (Kibele, 1999).

Equation 8-

$$\Delta y = \frac{Fmax t_c^2}{m\pi^2} + g\,\frac{t_c}{8}$$

Where:

Fmax= Maximal force

t_c= Contact time

m = Mass of body

g = Gravity

Equation 9-

$$a_v = \left(\frac{Fmax}{m}\right) - g$$

Where:

a_v= Vertical acceleration

F_{max}= Maximal force

m = Mass of body

g = Gravity

Furthermore, there are several problems associated with using force plate data in jumping analysis as there is no continuous function with a definite double integral (Kibele, 1999). External errors in force plate electronic and analog to digital conversions can result in rounding errors, errors in defining the time marker and points of maximum and minima. This can lead to underestimations and overestimations of the centre of mass displacement when calculated from force plate data through the double integration of vertical acceleration (Kibele, 1999).

It has been established that 3 dimensional motion capture is the gold standard practice for determining centre of mass displacement during movements by tracking the displacements of joint markers through the mid stance phase of movement (Orendurff, Segal, Klute, & Berge, 2004). Centre of mass displacement was calculated via segmental analysis. Each segment assessed was allocated a percentage of the individual's total body mass based on anthropomorphic data obtained from the use of Dempster (Winter, 2005). In order to successfully calculate the centre of mass displacement it was required that the location of each segments centre of mass along the long axis and radius of gyration were taken from Dempster (Winter, 2005). The advantage of implementing this method meant that the estimated displacement took into account both vertical and horizontal displacement through the analysis of each segments movement in relation to one another.

2.3.5 Methods of Calculating Joint Stiffness

To date there are two methods of determining joint stiffness, with details of these provided below along with Table 2.4.

1- Farley, Houdijk, Van Strien & Louie (1998) and Stefanyshyn and Nigg (1998) derived joint stiffness from the use of force plates and high speed video. Markers were placed on key anatomical landmarks and digitised in order to calculate joint angular displacements, velocities and accelerations. Inverse dynamics allowed for the measurement of joint moments of the hip, knee and ankle. Research evaluating joint stiffness has predominately utilised this methodology (Equation 10). Additionally, Stefanyshyn and Nigg (1998) fitted a linear regression equation to the joint moment and joint angle curve to determine the slope and joints stiffness of subjects.

Equation 10 –

$$K_{Joint} = \frac{J_m}{J_d}$$

Where:

J_m = change in joint moment from initial contact to where the centre of mass reaches its lowest point during ground contact.

J_d= joint angular displacement during the eccentric phase of movement

2- Arampatzis et al. (1999) proposed an alternative method of determining joint stiffness. Stiffness of the joint was defined as the ratio of negative mechanical work to the change in joint angle and required the use of kinetic and kinematic analysis (Equation 11). Research has questioned this methodology speculating it was not appropriate to divide an integral of work by the change in joint angle (Gunther & Blickhan, 2002).

Equation 11-

$$K_{Joint} = \frac{2W^-}{\Delta\theta}$$

Where:

$2W^-$ = negative mechanical work

$\Delta\theta$ = change in angular displacement

Table 2.4- *Summary of Joint Stiffness Calculations (Adapted from Butler et al., 2003).*

	Equation	Reference	How to Measure
1	$$K_{Joint} = \frac{J_m}{J_d}$$ Where J_m = change in joint moment from initial contact to where the centre of mass reaches its lowest point during ground contact; J_d= joint angular displacement during the eccentric phase of movement	Farley et al., (1998)	Force plate and high-speed video camera
2	$$K_{Joint} = \frac{2W^-}{\Delta\theta}$$ Where $2W^-$ = negative mechanical work; $\Delta\theta$ = change in angular displacement	Arampatzis et al. (1999)	Force plate and high-speed video camera

2.3.6 Investigated Athletic Populations and Tasks

In an attempt to profile vertical, leg and joint stiffness in athletic populations, research has predominately focused on the assessment of males during basic jumping tasks (Arampatzis et al., 2004; Boullosa et al., 2011; Harrison et al., 2004). Basic jumping tasks have included countermovement jumps, squat jumps, drop jumps and horizontal jumps (Arampatzis et al., 2004; Boullosa et al., 2011; Harrison et al., 2004; Hunter & Marshall, 2002; Moresi, Bradshaw, Greene, & Naughton, 2011). In addition, dynamic repetitive hopping tasks have also been assessed as they serve as a simplistic field based measure (Hobara, Inoue, & Kanosue, 2013; Hobara et al., 2008; Hobara, Kimura, et al., 2010; Pruyn et al., 2012; Pruyn et al., 2013; Watsford et al., 2010). Limited research has investigated how various athletic populations differ in leg stiffness, control strategies and the adaptations to tasks relevant to their training. Of the studies which have evaluated athletic populations sprint and endurance athletes were the most common (Boullosa et al., 2011; Bret, Rahmani, Dufour, Messonnier, & Lacour, 2002; Harrison et al., 2004; Hobara, Inoue, et al., 2010; Hobara et al., 2008; Kuitunen, Komi, et al., 2002; Song, Peng, Kernozek, & Wang, 2010; Stefanyshyn & Nigg, 1998). Additionally, general runners (those who run anywhere between 100 m sprint to 50 km) or recreationally active/control athletes are also commonly evaluated. Subsequently, the practical application and relevance of existing knowledge to high level athletes of potential performance benefits, appropriate monitoring tool and injury risk identification is limited.

There are multiple methodologies which have utilised various types of equipment in the quantification of stiffness in both field and laboratory settings. Despite variances in measures and techniques utilised by researchers to quantify leg and joint stiffness, research has established links between stiffness, performance and injury risk. Methods of determining variables associated with injury risk are key in high performance sport to provide relevant information to athletes and coaches of ways to enhance performance and reduce days lost to injury.

2.4 Relevance of Stiffness in High Performance Sport

Athlete screening and monitoring is key in high performance sport in order to provide relevant information to athletes and coaches on ways to enhance performance and minimise the risk of injury. Quantification of lower extremity stiffness provides an objective measure of a musculoskeletal response to load and has known links to both performance and injury. However, the knowledge regarding the influence of chronic athletic training is limited.

2.4.1 Influence of Athletic Training on Stiffness

Athletic training aids in the development of lower limb and joint stiffness modulation strategies such as the musculoskeletal system, neuromuscular control, co-contraction and regulation of muscle activity (Ambegaonkar et al., 2011; Kuitunen, Avela, et al., 2002; Kuitunen et al., 2007;

Kuitunen et al., 2011). These factors subsequently influence the overall kinematic and kinetic modulation strategies utilised by athletes to meet performance demands. Performance demands and conditioning varies amongst athletic training backgrounds were athletes may vary in intensity, duration and specific training types. As a result of the varying training regimes, athletic populations develop different kinematic and intrinsic muscle properties. Research has suggested sprint athletes are likely to have greater ratios of fast twitch muscle fibres whereas in contrast endurance athletes who predominately exhibit great ratios of slow twitch muscle fibres (Bushnell & Hunter, 2007).

Limited research has been undertaken to assess high level athletic populations. Recent research has established differences in leg stiffness between endurance trained athletes and untrained subjects in two legged hopping (Hobara, Kimura, et al., 2010). It was hypothesised that muscle stiffness has a dependency on neuromuscular adaptations and that the intrinsic differences in muscle function could account for stiffness differences between trained and untrained individuals. It was established for instance that leg stiffness levels were significantly greater in endurance athletes than untrained athletes. Athletes accomplished this through significantly greater joint stiffness at both the ankle and knee joints; while hip stiffness showed no differences between the two groups. Endurance athletes are believed to exhibit higher ratios of slow twitch muscle fibres allowing athletes to achieve higher levels of stiffness (Bushnell & Hunter, 2007; Hobara, Kimura, et al., 2010). The results from Hobara, Kimura et al. (2010) demonstrated that athletic training of endurance athletes enhanced stiffness production through the associated modulation strategies and intrinsic properties of the muscles fibres. Additionally, leg spring behaviour and impulse parameters were evaluated in elite expert jumpers and novice subjects during a run and jump test (Laffaye et al., 2005). Results highlighted that athletic training influenced stiffness behaviour where clear differences were observed between expert and novice jumpers in the contributions of leg stiffness to jump height and differing jump profiles. However, given the somewhat controlled hopping and jump task utilised in the previous studies, it remains unclear how athletic training influences the modulation strategies of athletes in functional tasks relevant to an athlete's habitual training background.

Investigation of locomotive differences between sprinters and endurance runners established kinematic variations to meet performance demands (Bushnell & Hunter, 2007). It was found that sprint athletes aimed to reach maximal speeds with little consideration of running economy. In contrast, for endurance athletes the maintenance of sub maximal speed is key in preserving running economy. The kinematics of distance running reveals the uniqueness of this event in regards to its economic efficiency. Athletes aim to increase stiffness of the global leg spring in order to maximise running economy through minimal vertical oscillation of the centre of mass and minimal joint flexion, while the upper extremity's primary function is to provide proper counterbalance (Bushnell & Hunter, 2007). Muscles, skeletal structures and organs of distance runners are physiologically adapted to manage long periods of stress on the body (Bushnell & Hunter, 2007; Hobara, Kimura, et al., 2010). Distance and endurance runners are able to alter their kinematics to ensure that movement patterns are economically efficient enabling them to maintain/improve performance, where the body is positioned in a manner such that foot contact keeps the braking forces to a minimum (Bushnell & Hunter, 2007). While performance demands of sprinters require athletes to produce powerful and explosive movements at maximal speeds, as a result are more capable of producing high speeds with greater acceleration (Bushnell & Hunter, 2007). During sprint performance sprinters achieved this through altered segment kinematics through a greater range of motion at the hip joint during flexion (Bushnell & Hunter, 2007).

It appears that intrinsic muscle properties, kinetics and kinematics differ between athletic populations, thus it can be suggested that athletic training influences the mechanical properties of an athlete, such as stiffness of the leg spring and the associated modulation strategies utilised. This highlights the importance of the need to investigate how different athletic populations regulate stiffness in tasks and conditions specific to their training and conditioning and the associated injury risk.

2.4.2 Stiffness and Performance

Research has recently established links between stiffness properties and performance, where optimisation of leg and joint stiffness is necessary to facilitate athletic performance. In order to optimally store and return elastic energy via the stretch shortening cycle in the musculoskeletal system during the loading phase of movement (mid-stance phase), a desired level of stiffness is necessary (Butler et al., 2003). As performance demands increase, there is an increased need for higher levels of stiffness in order to provide a greater resistance to muscle length change under a greater load in order to achieve controlled movements.

The interrelationship between stiffness and performance in hopping tasks is well established, whereby, as hopping frequency increased stiffness also increased (Farley, Blickhan, Saito, & Taylor, 1991; Granata et al., 2002; Hobara et al., 2013; Hobara, Inoue, Omuro, Muraoka, & Kanosue, 2011). Furthermore, a relationship between unilateral hopping forward velocity and stiffness was also apparent. Increases in hopping speed from 1.0 to 3.0 m/s, resulted in significant increases in vertical stiffness from 20 to 40 kN/m (Farley et al., 1991). Increased vertical stiffness results in decreased contact time, increased vertical velocity and increased hoping frequency, leading to an increased rate of force development during the stance phase of movement. This allows the individual to increase hopping height and overall performance. Similar notions were theorised by Granata et al. (2002) where it was suggested that to maintain a constant hop frequency in a mass spring model, stiffness must increase in order to support the increased loads placed on the system. Increases in hopping frequency resulted in increases in vertical stiffness to oscillate the system's mass, which is essential to resist the collapse of the leg during landing.

Furthermore, increases in vertical stiffness during repetitive hopping have been attributed to the modulation of the joint angles of the lower limb at touchdown (Hobara, Kimura, et al., 2010). Similarly, it has been shown that increased leg extension at initial contact allows for the ground reaction force vector to be in alignment with each joint, resulting in decreased joint moments while stiffness increased (Kuitunen, Komi, et al., 2002). A similar finding was reported by McMahon et al. (1987) where it was found that groucho running (running with a greater degree of knee flexion than usual) showed significant declines in vertical stiffness. Furthermore, it was proposed that subjects that maintained a more erect posture achieved a stiffer landing, while subjects that showed greater flexion in each joint in order to prepare/soften the landing impact, therefore decreasing stiffness levels (DeVita & Skelly, 1992). Greater degrees of flexion results in a greater displacement of the centre of mass, leading to decreased stiffness, thus reducing the ability of the limb to resist change resulting in compromised performance and potentially increasing an individual's susceptibility to injury (DeVita & Skelly, 1992; Granata et al., 2002; Hobara, Kimura, et al., 2010; McMahon et al., 1987; Padua et al., 2006). Research has suggested reduced stiffness is linked to injury as there may be increased stress placed on the muscle due to increased need to regenerate force during contact (Butler et al., 2003).

Increased lower extremity stiffness during running has been associated with critical performance measures such as stride frequency, stride length, (Farley & Gonzalez, 1996), running speed (Kuitunen, Komi, et al., 2002), running economy (Dutto & Smith, 2002; McMahon & Cheng, 1990), contact time and flight time (Butler et al., 2003). It has been speculated that increased stiffness enhances running performance within a limit. In contrast it has been postulated that higher stiffness levels may be detrimental to performance in higher loading drop jump tasks (Walshe & Wilson, 1997). Furthermore, in long jumping there appears to be an optimal range of mechanical stiffness where increasing stiffness may not, in turn, increase jump distance (Seyfarth, Geyer, Gunther, & Blickhan, 2002) thus, highlighting the notion that an optimal range of lower extremity stiffness may exist for maximal performance. Additionally, it has been speculated that fatigue may contribute to decreased vertical and leg stiffness in treadmill running resulting in decreased running economy (Dutto & Smith, 2002).

Research has investigated the continuous change in spring-mass characteristics during sports-specific performances, for example a 400 m sprint (Hobara, Inoue, et al., 2010). Performance in these events utilises the anaerobic energy stores to their limit along with a substantial portion of aerobic energy stores (Ackland et al., 2009; Bushnell & Hunter, 2007; Hobara, Inoue, et al., 2010). Postponing the onset of fatigue is a desirable attribute of 400 m runners, as it allows for the maintenance of stride frequency and length contributing to higher running velocities and thus performance. Changes were observed in vertical and leg stiffness over the entire duration of a 400 m performance particularly between stiffness, running velocity, stride frequency and stride length. Since the correlations between vertical stiffness and forward velocity were evident during the entire 400 m sprint it can be suggested that vertical stiffness may not only play a significant role in maintaining forward velocity in treadmill running but also affect field running performance. Maximal values of vertical stiffness and forward velocity were found to occur between the 50 – 100 m interval while consistent decreases in both vertical stiffness and forward velocity occurred from the 50 – 100m interval to the 350 – 400m intervals. This suggests that vertical stiffness decreases with fatigue and may be a limiting factor in 400m sprint performance. Vertical stiffness was also found to play an important role during the later stages of the 400 m run. High levels of vertical stiffness allow the runner to maintain a high stride frequency which results in higher running velocities (Hobara, Inoue, et al., 2010). However, the majority of participants in this study were 100 - 110 m sprint or endurance specialists and were not accustomed to the demands of 400 m sprints and as a result may have been limited in their ability to anticipate task demands and adapt accordingly.

Accordingly, it can be suggested that habitual training of athletes assists in the development of necessary muscular and mechanical changes required to maintain optimal levels of stiffness required to meet performance demands (Dutto & Smith, 2002). Table 2.5 summaries the relationship between stiffness and performance.

Table 2.5- *Summary of the relationship between stiffness and performance (Adapted from Butler et al., 2003).*

Activity	Result	Studies
Hopping		
Increased lower extremity stiffness	• Increased hopping frequency	Farley et al. (1991), Granata et al. (2001)
Running		
Increased lower extremity stiffness	• Increased running velocity	Arampatzis et al. (1999), Seyfarth et al. (2002), Stefanyshyn and Nigg (1998), Farley and Gonzalez (1996)
	• Decreased stride length	McMahon and Cheng (1990), Derrick et al. (2000), Kerdock et al. (2002)
	• Decreased energy requirement	McMahon and Cheng (1990), Dutto and Smith (2002), Heise and Martin (1998), Farley and Morgenroth (1999)
	• Increase in treadmill speed running	He et al. (1991), Morin et al. (2005), McMahon and Cheng (1990)
Decreased vertical stiffness	• Decrease treadmill speed running	Dutto and Smith (2002)
	• Decrease forward velocity	Hobara et al. (2010a)

2.4.3 Stiffness and Injury

It appears there is an optimal amount of stiffness which allows for enhanced performance, however too much or too little stiffness may lead to increased risk of injury (Brughelli & Cronin, 2008a; Butler et al., 2003). Increased stiffness can be achieved through increased peak forces and a decrease in lower extremity displacements. Subsequently increasing stiffness levels also increases the loading rates on the lower extremity, as a result enhancing the risk of bone injury due to the increased shock on the lower extremity (Butler et al., 2003). Too little stiffness decreases the ability of the lower extremity to resist deformation to a given force which has shown to occur under fatigued conditions (Butler et al., 2003; Granata et al., 2002; Padua et al., 2006). Accordingly, there is a greater degree of excessive movement around the joint resulting in a need to regenerate the force that is dissipated as heat and consequently a larger degree of centre of mass displacement (Butler et al., 2003), and increased musculoskeletal injury risk (Butler et al., 2003; Granata et al., 2002; Padua et al., 2006). Given the links between stiffness and injury, identification of high risk athletes through lower limb stiffness profiling may be beneficial, however research has typically focused on assessing male athletes during basic jumping tasks (Arampatzis et al., 2004; Boullosa et al., 2011; Harrison et al., 2004). Research has established, females display an impaired ability to regulate stiffness and as a result are at an increased risk of injury (Granata et al., 2002; Padua et al., 2006). Due to the known links between stiffness and injury, evaluation of stiffness modulation strategies of female athletes is of particular necessity as they are under-reported in stiffness research and are at risk of injury incidence (Padua et al., 2006).

Varying levels of stiffness affect athletic injuries; i) low levels of stiffness can be coupled with soft tissues injuries and ii) excessively high levels of stiffness can be associated with bone injuries (Butler et al., 2003). An athlete’s habitual training background may predispose them to an elevated risk of specific types of injuries. It has been speculated endurance runners may be more susceptible to overuse bone related injuries due to a multitude of contributory factors such as elevated level of lower limb stiffness and high training volumes (Hobara, Kimura, et al., 2010). Understanding how different training routines and types of athletic training interact to affect leg stiffness in varying conditions is important to assist in the development of effective monitoring tools to allow for the early identification and implementation of preventative strategies for at risk athletes. Female athletes are believed to be at an elevated risk of injury incidence when compared to their male counterparts due to reduced levels of lower extremity stiffness (Padua et al., 2006). Despite being known to be at an increased risk of injury, female athletes are under reported in stiffness literature (Granata et al., 2002; Padua et al., 2006).

Research evaluating longitudinal stiffness changes in relation to injury incidence have primarily focused on assessing athletic populations through the use of repetitive hopping tasks (Hobara, Kimura, et al., 2010; Pruyn et al., 2012; Pruyn et al., 2013; Watsford et al., 2010). Emerging research evaluating seasonal changes in Australian Rules footballers during hopping have proposed the notion that a significantly higher mean bilateral stiffness difference appeared to place athletes at an increased risk of soft tissue injuries particularly hamstring strains (Pruyn et al., 2012; Pruyn et al., 2013; Watsford et al., 2010). It is important to note no changes in stiffness were evident across a season of training nor did it appear significantly related to injury incidence (Pruyn et al., 2012). Additionally, recent research investigating Australian Rules footballers has suggested that stiffness appeared unrelated to lower limb muscle strain injury (Serpell, Scarvell, Ball, & Smith, 2014), however despite somewhat simplistic jumps testing, results approached statistical significance ($p=0.08$). As a result, it remains plausible that stiffness and soft tissue injury may indeed be related. It is assumed that stiffness evident during repetitive hopping is reflective of stiffness measures during the daily training and competition environment, however, it is unclear if this is the case. Further research is required to examine the relationships between stiffness and performance or injury from the use of sports-specific tests rather than low-intensity, generic hopping assessments.

Limited research has investigated longitudinal changes in lower extremity stiffness and the associated risk of injury in athletic populations during tasks relevant to the habitual training background of athletes. Additionally, there is a need to identify appropriate monitoring tools in order to provide relevant information to coaches and athletes on way to optimize stiffness and minimize injury risk.

2.5 Summary of Literature Review

Stiffness of the lower-extremity has the ability to describe the relationship between the amount of leg flexion and the external load subjected to the limb. Quantification of lower-extremity stiffness allows for the measurement of a complex system of joints, muscles and tendons of the lower limb to be modelled as a simple linear spring. Researchers have utilised a variety of methodologies to determine stiffness in predominately laboratory settings, however there have been limited field based studies assessing stiffness. There are a variety of positives and negatives associated with each method. Despite technical variations utilised to quantify stiffness, literature has established clear links between stiffness, performance and injury. However, these measures appear isolated to a laboratory setting during basic jumping tasks, which may limit the practical application to high performance athletic populations.

It appears that leg stiffness, joint stiffness and the associated control strategies are influenced by athletic training. Despite suggestions athletic training influences lower extremity stiffness, limited research has been undertaken to evaluate athletes from varied training background and to longitudinally track stiffness changes. It appears lower extremity stiffness is potentially related to performance and injury and may be relevant monitoring tool for practitioners in high performance sport. In light of the research literature to date the implications of these variables on athlete screening and monitoring for injury identification remain unclear. Thus, there is a need to systematically review and evaluate the gaps in the literature:

1. Populations that have been assessed in relation to training development and athletic practice,
2. Tasks that have been utilised to evaluate stiffness difference between groups, and
3. Assess the underlying mechanisms which have been utilised to evaluate lower extremity stiffness modulation.

Chapter 3. Systematic Review

The systematic review was undertaken at the conception phase of this thesis to provide a framework for gaps in stiffness literature to be addressed. Although the systematic review was current at the time of writing, the authors acknowledge that further stiffness research among athletic populations has been published. For the purpose of the thesis this chapter provided clear systematic guidance for the research process. The findings are still relevant in regards to stiffness literature; however recent additional relevant articles have been included in the narrative review of the literature.

3.1 Introduction

Lower-extremity stiffness describes the deformation of the body under an applied force and enables the muscle to increase its resistance to change under an applied load (Brughelli & Cronin, 2008a, 2008b). Researchers have applied this concept to the study of human locomotion, whereby links between performance benefits and injury risk have been established (Ambegaonkar et al., 2011; Bret et al., 2002; Hobara, Inoue, et al., 2010; Hobara, Kimura, et al., 2010; Kulig, Fietzer, & Popovich, 2011; Watsford et al., 2010). Athletic training has been found to modulate muscle development, kinematic strategies, muscle activation patterns, and central nervous system feed-forward mechanisms (Bushnell & Hunter, 2007; Hobara, Kimura, et al., 2010). These physical training changes can influence the strategies individuals employ to modulate stiffness during movement according to task demands. By profiling differences in lower-extremity stiffness in athletic populations and the stiffness strategies athletes employ, researchers have gained an understanding of the mechanics that various populations employ to meet task demands (Kuitunen, Komi, et al., 2002).

To improve athletic performance, reduce injury risk or control the mechanical interaction of the musculoskeletal system and surrounding environment during the ground-contact phase of movement, optimal levels of functional stiffness such as joint, leg and vertical stiffness are needed

(Brughelli & Cronin, 2008a, 2008b). Optimal lower-extremity stiffness increases the storage and return elastic energy via the stretch shortening cycle (Hobara, Inoue, et al., 2010; Kuitunen, Avela, et al., 2002; Rabita, Couturier, & Lambertz, 2008; Slawinski, Heubert, Quievre, Billat, & Hannon, 2008), whereby higher levels of elastic energy and rapid transmission of applied forces allow maximised performance. In contrast, lower levels of stored elastic energy; more energy dissipated as heat; and prolonged transmission of forces may increase injury risk (Burgess, Connick, Graham-Smith, & Pearson, 2007; Hobara et al., 2008). Stiffness of the lower limb can be described through the spring mass model which represents the lower limb as a simple single linear spring and entire body as a mass, where force is required to stretch or compress the spring. This model allows for the mechanics of running gait, applied lower-extremity stiffness estimations and reciprocal relationship between ground contact time, stride frequency, technique changes and landing velocity to be measured (Brughelli & Cronin, 2008b; Slawinski et al., 2008).

The optimisation of lower-extremity stiffness along with the storage and return of elastic energy is dependent upon the capacity of the muscle to produce force and the rate force production (Kuitunen, Avela, et al., 2002). Force production and transmission can be efficiently modulated through neural muscular control strategies and co-contraction of bi-articular muscles (Hobara et al., 2008; Kuitunen, Komi, et al., 2002) enabling individuals to achieve the maximal force output or muscular economy necessary to sustain repetitive bouts of exercise (Kuitunen et al., 2007). Neural regulation of lower-extremity stiffness is influenced by intrinsic properties, muscle twitch times, rate of torque development, intrafusal fibre development and golgi tendon organ size and number (Butler et al., 2003; Morin et al., 2006; Rabita et al., 2008; Toumi et al., 2004). These physiological properties and neural adaptations can be developed through training (Butler et al., 2003; Morin et al., 2006; Rabita et al., 2008; Toumi et al., 2004), although defining and assessing the augmentation of stiffness from training history in a variety of athletic populations requires further investigation.

Given that athletic training aids the development of the musculoskeletal system and neuromuscular control strategies, it also regulates the overall muscle activity and individual kinematic strategies, ultimately influencing the regulation of stiffness (Ambegaonkar et al., 2011; R. Clark, 2009; Kuitunen, Avela, et al., 2002; Kuitunen et al., 2007; Kulig et al., 2011). For example, in running, sprinters alter their segment kinematics through greater ranges of motion at the hip joint during flexion in order to achieve maximal running speeds with little consideration for economy (Bushnell & Hunter, 2007). In contrast, endurance runners aim to increase leg stiffness in order to preserve running economy through minimal vertical oscillation by using minimised joint flexion (Bushnell & Hunter, 2007; Hobara, Kimura, et al., 2010). Reduced joint flexion is achieved through effective hip and knee extension before ground contact allowing for toe contact to be located closer to underneath the body and hips (Hobara, Inoue, et al., 2010).

Sub-optimal lower-extremity stiffness can place individuals at higher risk of injury (Hobara, Inoue, et al., 2010; Hobara, Kimura, et al., 2010; Watsford et al., 2010). Higher levels of stiffness can result in an increased risk of bone-related injuries, due to the associated rapid transmission of high ground reaction force from muscle to bone (Butler et al., 2003; Hobara, Kimura, et al., 2010). Conversely, lower levels of stiffness may increase the individual's risk of soft tissue injuries as the time taken for the force transmission to occur is increased (Butler et al., 2003). Thus, it has been suggested that an athlete's habitual training background may place an individual at greater risk of specific types of injuries. Endurance athletes are known to display higher levels of lower-extremity stiffness and consequently have a higher prevalence of stress fractures and bone related injuries (Hobara, Kimura, et al., 2010). This occurs due to the kinematic, kinetic and subsequent stiffness attenuation strategies that are associated with an individual's training background and task demands, whereby modulation of lower-extremity stiffness is reliant upon these factors (Komi, 2000).

To date it appears research has focused on assessing single athletic populations or profiling athletes as an entire demographic during conventional maximal countermovement jumps, maximal drop jumps or running tasks. It has been established that differences in muscle activation patterns and stiffness values between recreational, power-trained and endurance-trained athletes exist (Boullosa et al., 2011; Girard, Millet, Slawinski, Racinais, & Micallef, 2010; Harrison et al., 2004; Hobara et al., 2008; Hobara, Kimura, et al., 2010). Limited research has been undertaken to review the methodology and findings of the literature which has investigated the effect of chronic athletic training on lower-extremity stiffness. Therefore, the purpose of this study was to systematically review and evaluate the existing knowledge of vertical, leg and joint stiffness in the lower-extremity in relation to training development and athletic practice in adult populations. Secondly this study aimed to assess methods used to quantify the relationship between lower-extremity stiffness and athletic training.

3.2 Methods

Three primary research databases (SPORTDiscus, Medline and CINAHL) were identified and searched by one author (EM). A seven level search strategy (S1-7) was developed and implemented to systematically search and retrieve all available publications from the databases related to lower-extremity stiffness and athletic training (Table 3.1). The terms “joint stiffness” (S1), “leg stiffness” (S2), “vertical stiffness” (S3) and “spring mass” (S4) were searched in the title (TI), abstract (AB), keyword (KW) and text (TX) as these select terms are commonly used phrases that portray applied measures of lower-extremity stiffness. The search terms for (S6) were derived by selecting all relevant terms related to athletic training and practice from the SPORTDiscus sport thesaurus and were then matched with its equivalent/related Medline MeSH terms and CINAHL headings. Where possible all search terms were exploded to allow for all primary and subsequent secondary terms to be systematically searched throughout the literature. While clinical trials were not the primary study design focus of this review, the Cochrane group clinical trial database CENTRAL was searched to ensure all relevant databases were reviewed (see Table 3.2 for search strategy). Where possible all searches were limited to human and peer-reviewed studies. An initial search was conducted on 3/8/2011, with a secondary search to undertaken on 2/12/2011 in order to retrieve any relevant publications since the initial search.

Table 3.1 - *Search Strategy for SPORTDiscus, MEDLINE and CINAHL Database.*

S1-	TI "joint stiffness" or AB "joint stiffness" or KW "leg stiffness" or TX "joint stiffness"
S2-	TI "leg stiffness" or AB "leg stiffness" or KW "leg stiffness" or TX "leg stiffness"
S3-	TI "vertical stiffness" or AB "vertical stiffness" or KW "vertical stiffness" or TX "vertical stiffness"
S4-	TI "spring mass" or AB "spring mass" or KW "spring mass" or TX "spring mass"
S5-	S1 or S2 or S3 or S4
S6-	(MH "Physical Education and Training +") or (MH "Resistance Training") or (MH "Athletic Training +") or (MH "Sport Specific Training") or DE "Training" or DE "Bounding" or DE "Long-Term Athlete Development" or SU Training or TI Training or AB Training or KW Training or TI Athlete or AB Athlete or KW Athlete or SU Athlete or SU Athletics
S7-	S5 and S6

S1-S7- Search 1 to Search 7, TI- Title, AB- Abstract, KW- Key word, TX- Text, MH- Main heading, DE- Descriptors, SU- Subject.

Table 3.2 - *Search strategy for Cochrane CENTRAL database.*

S1-	TI "joint stiffness" or AB "joint stiffness" or KW "leg stiffness" or TI "leg stiffness" or AB "leg stiffness" or KW "leg stiffness" or TI "vertical stiffness" or AB "vertical stiffness" or KW "vertical stiffness"
S2-	(MH "Physical Education and Training +") or (MH "Resistance Training") or (MH "Athletic Training +") or (MH "Sport Specific Training") or (MH "Athletic Performance +")
S3-	S1 and S2

S1-S3- Search 1 to Search 3, TI- Title, AB- Abstract, KW- Key word, MH- Main heading.

The search strategy retrieved 290 abstracts of studies potentially suitable for inclusion. All results and related abstracts were then imported into the reference manager EndNote (Thomson Reuters, New York USA). Following the removal of 16 duplicates, the results were then reduced to 274 relevant articles that were then reviewed by one author (EM) to remove articles deemed ineligible based on the title and abstract. Full text sources of the remaining 92 articles where then obtained and reviewed by two authors (EM and RL) who worked independently to assess the relevance of articles for inclusion, based on the outlined inclusion criteria (Table 3.3). Any inconsistencies in regard to eligibility of articles where resolved by discussion and agreement between the two authors. Following full text review, 24 articles were identified that met the inclusion criteria. Manual search of each included article reference list was undertaken by one author (EM) to identify any further articles that meet the inclusion criteria based on TI and AB. Full text articles where again retrieved and assessed by two authors (EM and RL) for relevance. This process resulted in a further seven articles included for review. Using a standardised data extraction sheet; created using Microsoft Excel (Microsoft Corporation, Redmond WA); one author (EM) extracted all relevant information from the final list of 31 full text articles (Figure 3.1).

Table 3.3- *Inclusion and Exclusion Criteria.*

Inclusion Criteria	**Exclusion Criteria**
Human studies Healthy populations Adult/fully developed/physical matured populations English studies Lower – extremity/lower limb/lower leg (include anatomical areas of thigh/upper leg, lower leg, ankle, foot, knee, hip and associated muscles) Experimental, intervention and descriptive studies that assess the following impact on stiffness • Effects of sporting related fatigue and exhaustive exercise • Training intervention studies • Studies which include athletes and stiffness attenuation strategies Applied measures of stiffness • Vertical stiffness- peak vertical force divided by maximum vertical displacement (i.e. McMahon and Cheng (1990), McMahon et al (1987), Cavagna et al., (1988) and Morin et al., (2005)) • Leg stiffness- peak vertical force divided by change in vertical leg spring length (i.e. McMahon and Cheng (1990) and Morin et al., (2005)) • Joint stiffness- ratio of joint moment to angular joint displacement (i.e. Farley et al., (1998), Stefanyshyn and Nigg (1998) and Arampatzis et al., (1999))	Animal Studies Non healthy populations • Injured • Neurological or neuromuscular pathology • Diseased Children, youths, impended, disabled or temporarily disabled. Non English studies Upper-extremity studies Studies that inferred muscle stiffness response but do not directly measure stiffness Review and methodological papers Experimental, intervention and descriptive studies that assess the following impact on stiffness: • Influence of bracing, shoes, taping, prosthesis and orthoses • Genetics • Studies which look at the physiological effects on stiffness i.e. female menstrual cycle • Rehabilitation studies Non-movement stiffness studies • Physiological based studies i.e. arterial stiffness • Stiffness as a measure of pain i.e. stiffness of a joint Clinical measures of stiffness • Muscle-tendon stiffness - the oscillation technique • Tendon stiffness - ultrasonography (slope of the force-tendon length curve) and isokinetic dynamometer to measure joint torque. • Passive stiffness – isokinetic dynamometer

*Articles which contain both elements of the inclusion and exclusion criteria will be included for review.

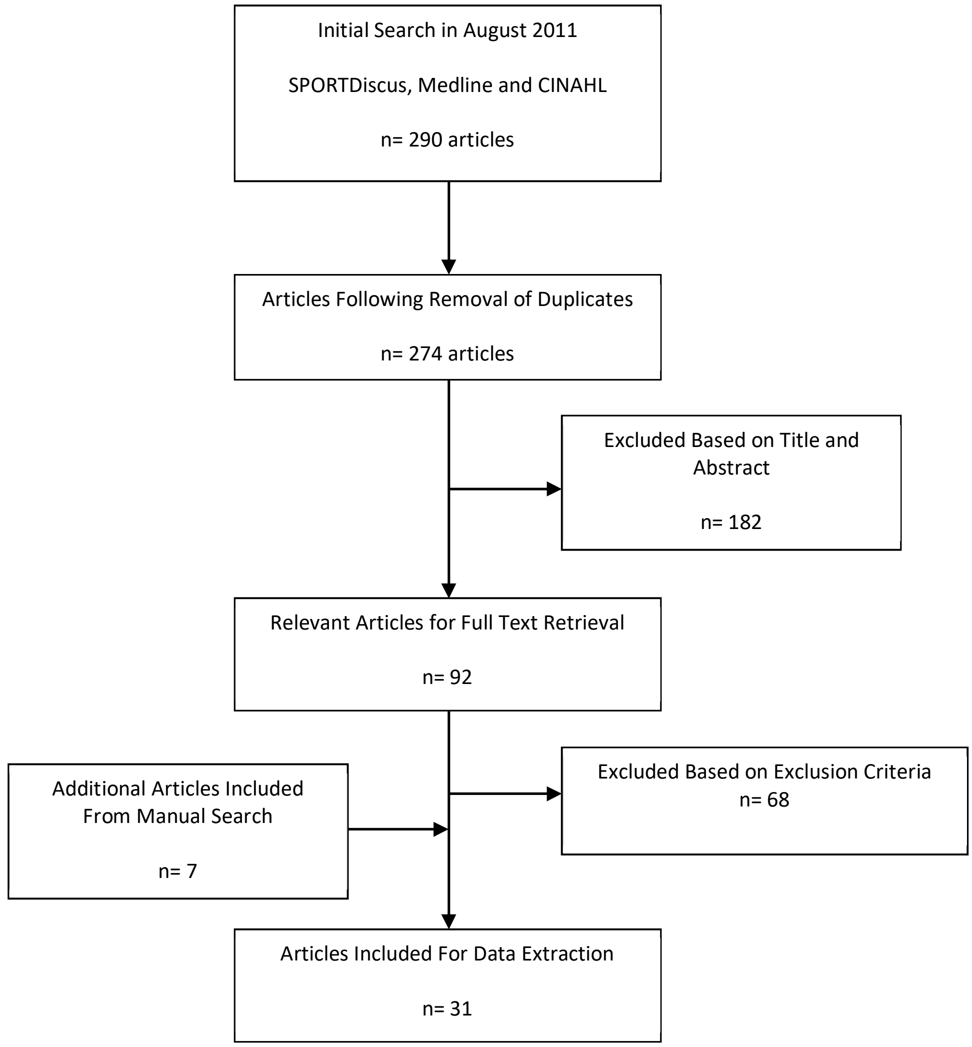

Figure 3.1- Flowchart of study inclusion.

Following data extraction, a customised version of the Strengthening the Reporting of Observation Studies in Epidemiology (STROBE) criteria was applied in order to assess the quality of reporting of the applicable articles (Von Elm et al., 2007) (Appendix A). The STROBE criteria was used as the included articles were similar to epidemiological study designs. Articles were allocated a percentage score that was representative of the raw score divided by all relevant criteria. The score reflected the quality of reporting and did not necessarily reflect the quality of the investigation, design and/or methods of the studies itself.

3.3 Results

The data displayed in Table 3.4 shows the extracted information including the populations recruited, sample size, gender, age range, main objectives and study design of the included articles. A majority of the studies utilised a cross sectional design (27), while the remaining studies employed a longitudinal (3) or a case-control design (1). All longitudinal studies incorporated the use of training interventions in order to assess the impact of training on lower-extremity stiffness attenuation.

Few studies aimed to assess differences in lower-extremity stiffness and control strategies utilised between multiple sub-populations (8). Whilst the remaining studies aimed to assess the effect and interaction of an independent variable on lower-extremity stiffness (23). Total participant numbers ranged from 4 to 136 (mean N=20) and sub-population sample size ranged from 4 to 122 (mean n=16). A majority of the studies assessed male participants (15), while the remaining evaluated both genders (5), female participants (3) or did not report the gender investigated (8). Age of participants ranged for 18.9 to 29 years, however several studies did not report (5) the age of their participants (Arampatzis, Brueggemann, & Morey Klapsing, 2001; Arampatzis et al., 1999; Arampatzis, Schade, Walsh, & Brüggemann, 2001; Arampatzis et al., 2004; Slawinski et al., 2008). Populations recruited included sprinters (6), endurance (6), runners (4), athletes (3), football players (3), jumpers (2), dancers (2), basketball players (1), decathletes (1), gymnasts (1), tri-athletes (1) and handball players (1).

Table 3.4- *Objectives, Population Descriptive and Study Design of Articles Included for Data Extraction.*

Articles	Main Objective	Population	Sample	Sex	Age	Study Design
Ambegaonkar et al. 2011	To compare knee muscle activation patterns, leg spring and knee joint stiffness between female dancers and basketball players during drop jumps.	Dancers (D) and basketball (B) players	D- n = 35 B- n = 20	F	D- 20.7 (2.3) B- 20.1 (2.0)	CS
Arampatzis et al. 1999	To evaluate the influence of running speed on leg, ankle and knee spring stiffness.	Runners	N = 13	NR	NR	CS
Arampatzis, Brueggemann et al. 2001	To examine how a sprung surface affects the mechanical energetic processes of leg stiffness during drop jumps.	Athletes (specific population not reported)	N = 10	F	NR	CS
Arampatzis, Schade et al. 2001	To examine the effect of leg stiffness on mechanical power and take-off velocity during drop jumps.	Decathletes	N = 15	NR	NR	CS
Arampatzis et al. 2004	To assess the influence of surface on leg stiffness and performance during drop jumps.	Gymnasts	N = 10	F	NR	CS
Boullosa et al. 2011	To evaluate the mechanical differences between a counter movement jump before and after the Universite de Montreal Track Test in endurance athletes.	Endurance athletes (runners and triathletes)	N = 22	M + F	MR- 24 (4.3) FR- 22.5 (5.5) MT- 28.5 (6.2)	CS

Articles	Main Objective	Population	Sample	Sex	Age	Study Design
Bret et al. 2002	To investigate the relationship between leg strength and stiffness in 100m sprint performance within and between specific sprint phases.	100 m sprinters (split into two groups [G1 + G2] based on velocity)	G1- n = 8 G2- n = 11	M	G1- 22.5 (3.9) G2- 22.1 (4.0)	CS
Clark 2009	To compare joint stiffness of athletes with extensive eccentric training or recreational sporting background during repeated maximal intensity sprints.	Semi-professional rugby league players (Athletic training background [A]) and non-athlete (NA) recreational sporting participants	A- n = 11 NA- n = 11	NR	A- 22.1 (9.9) NA- 20.9 (2.3)	CS
Comyns et al. 2007	To examine the effect of three resistive loads on the performance of the fast stretch shortening cycle activity and to determine if an optimal resistive load exists in complex training.	Elite rugby players (contracted to national rugby football league)	N = 12	M	23.3 (2.5)	CS
Dutto et al. 2002	To evaluate stiffness characteristics changes during a fatiguing run.	Well trained runners (10 - 50 km)	N = 15	M + F	28.3 (6.7)	CS
Farley et al. 1996	To determine changes in the leg spring stiffness and angle swept by the leg spring during altered stride frequency at a given running speed.	Experienced treadmill runners	N = 4	M	21-29	CS
Girard et al. 2010	To assess the impact of varying athlete training status on fatigue-induced changes in spring-mass model characteristics during a 5000 m self-paced run.	Triathletes (split into highly trained [HT] and well trained [WT])	HT- n = 6 WT- n = 6	NR	HT- 22.7 (2.3) WT- 20.2 (2.3)	CS

Articles	Main Objective	Population	Sample	Sex	Age	Study Design
Harrison et al. 2004	To examine the stretch-shortening cycle function and control of leg-spring stiffness of sprint and endurance athletes during squat, countermovement, and drop rebound jumps on an inclined sledge apparatus.	Sprinters (100 m runners) (S) and endurance (national league 1500 m - 10000 m) (E)	S- n = 7 E- n = 7	M	S- 22.0 (2.7) E- 21.3 (2.5)	CS
Hobara, Inoue et al. 2010	To assess changes in vertical and leg stiffness over a 400 m sprint and its relationship to running velocity, stride frequency and/or stride length.	Well trained athletes (two 100m sprinters, one 110m hurdler, three 400m sprinters, one 800m runner and one endurance runner)	N = 8	M	22.4 (3.2)	CS
Hobara et al. 2008	To validate differences and overall mechanistic alterations in stiffness between two training modalities.	Endurance athletes (E)- distance runners and power-trained athletes (P)- sprinters	E- n = 7 P- n = 7	NR	E- 20.0 (1.2) P- 20.1 (1.5)	CS
Hobara, Kimura et al. 2010	To assess leg and joint stiffness differences between endurance and untrained populations during hopping.	Endurance runners- elite track distance runners (E) (5000 or 10000 m races) and untrained- sedentary (U)	E- n = 8 U- n = 8	NR	E- 19.9 (1.1) U- 24.3 (1.9)	CS
Hobara et al. 2009	To evaluate if knee joint stiffness is a major determinant of leg stiffness during maximal hopping.	Well trained athletes	N = 10	M	20.3 (1.4)	CS

Articles	Main Objective	Population	Sample	Sex	Age	Study Design
Hunter et al. 2002	To assess the effects of power training and stretching on unrestricted jump performance and technique.	Variety of training backgrounds primarily basketball and volleyball (randomly assigned to four groups; power [P], stretch [S], power and stretch [P+S] and control [C])	P- n = 11 S- n = 11 P + S- n = 14 C- n = 14	M	24 (4)	L
Hunter et al. 2007	To assess vertical and leg stiffness as a potential explanation for frequency changes with fatigue and determine if runners demonstrate a self-optimising capability when fatigued.	Not Reported	N = 16	M + F	28 (8)	CS
Kubo et al. 2007	To investigate the influence of plyometric and weight training protocols on the mechanical properties of muscle -tendon complex, muscle activities and performance during jumping.	Healthy	N = 10	M	22 (2)	L
Kuitunen et al. 2002	To investigate the stiffness regulation in the ankle and knee joint in sprinters at high running speeds.	Sprinters (100 m runners, elite)	N = 10	M	23 (4)	CS
Kuitunen et al. 2007	To evaluate muscle activity of the triceps surae muscle and its impact on leg stiffness during fatigued stretch shortening exercise.	Recreationally active	N = 8	M	25 (3)	CS
Kulig et al. 2011	To examine the vertical ground reaction forces and knee joint kinetics during the take-off and landing phases of sautés de chat in asymptomatic pre-professional dancers.	Dancers (jazz, ballet, modern and hip-hop)	N = 11	M + F	18.9 (1.2)	CS

Articles	Main Objective	Population	Sample	Sex	Age	Study Design
Laffaye et al. 2005	To investigate the effect of jumping expertise on leg spring behaviour during one-leg vertical jumps and the contribution of impulse parameters.	Expertise jumpers (fosbury athletes [F], volleyball [V], handball [H] and basketball [B] players). Control group (C) - novice (no prior jumping experience)	F- n = 4 V- n = 5 H- n = 4 B- n = 5 C- n = 5	M	F- 24.8 (3.0) V- 26.0 (6.9) H- 23.3 (4.8) B- 22.8 (2.9) C- 24.5 (4.2)	CS
Morin et al. 2006	To investigate spring mass model characteristics and interaction between mechanical parameters during maximal sprinting in field based conditions and associated changes due to fatigue.	Physical education students (not sprint running specialists)	N = 8	M	23 (4)	CS
Rabita et al. 2008	To evaluate the impact of different plyometric training background on ankle intrinsic stiffness and overall musculoskeletal stiffness performance during stretch shortening cycle type exercise.	Control group (C) (sedentary subjects) and athletic group (A) (elite long and triple jumpers)	A- n = 9 C- n = 9	NR	A- 24.5(3.9) C- 27.5 (5.2)	CS
Slawinski et al. 2008	To evaluate whether exhaustion modifies stiffness characteristics and to investigate whether stiffer runners are more economical.	10, 000 m competitive runners	N = 9	M + F	NR	CS
Song et al. 2010	To determine the changes in lower-extremity joint stiffness at different drop heights when jumping over a barrier.	Power-oriented track and field	N = 14	M	22.5 (3.5)	CS
Stefanyshyn et al. 1998	To assess the ankle joint moment-angle relationship and the apparent ankle joint stiffness during the stance phase of running and sprinting.	Competitive distance runners (D) and sprinters (S)	D- n = 5 S- n = 5	M	D- 22 (4) S- 22 (2)	CS

Articles	Main Objective	Population	Sample	Sex	Age	Study Design
Toumi et al. 2004	To compare the effects of jump performance and muscle strategy during squat and countermovement jump performance.	Handball players (split into 3 groups; weight training [WT], combined training [CT] and control [C])	W- n = 8 CT- n = 8 C- n = 8	M	W- 21 (2) CT- 20 (2) C- 21 (2)	L
Watsford et al. 2010	To investigate whether leg stiffness is a primary risk factor for hamstring injury.	Australian rules football players (non-injured [NI] and injured [I])	NI- n = 122 I- n = 14	NR	NI- 22.6 (3.5) I- 27.0 (4.3)	CC

M- Male, F- Female, NR- Not reported, CS- Cross sectional, L- Longitudinal, CC- Case control.

Table 3.5 illustrates the extracted data for the relative limb used and assessed during jump task, task type, number of trials performed, stiffness measure and the methods used to calculate stiffness. The type of movement task utilised to assess lower-extremity stiffness included hopping/jumping tasks (21), running/sprinting tasks (12), and tasks more specific to participants training background (1). Jump tasks included drop jumps aiming to achieve maximal height (10) that utilise a variety of drop heights [30 cm (4), 20 cm (3), 40 cm (3), 60 cm (3), 45 cm (1), 90 cm (1) and not reported (1)], maximal countermovement jumps (9), maximal repetitive jumps (6) and maximal squat jumps (4). Running tasks included studies which assessed sprinting (6) and aerobic running tasks (5). The running speed or jump frequency of which the movement task was performed included pre-determined running velocity or set jump frequency (10), self-selected running speed or jump frequency (1) and several studies did not report running speed or jump frequency of tasks (21). Lower Limb(s) utilised during tasks included either uni-lateral (19), bi-lateral (9) and did not report which limb/s used (9). Lower limb assessed to determine lower-extremity stiffness included dominant/preferred limb of participants (4), both left and right limbs (3), right leg only (3), uni-lateral stiffness but did not state the specific limb (1) and did not report which limb/s assessed (21). The number of trials utilised ranged from one to ten.

This review focussed on applied measures of lower-extremity stiffness. The systematic review process identified studies which evaluated applied stiffness measures which included leg and joint stiffness (7), leg and vertical stiffness (7), joint stiffness (6), leg stiffness (5), vertical stiffness (3), eccentric stiffness (1), vertical and joint stiffness (1) and all applied measures of lower-extremity stiffness i.e. leg, vertical and joint stiffness (1). Of the studies that assessed joint stiffness, joints evaluated included knee and ankle stiffness (6), hip, knee and ankle stiffness (3), knee stiffness (3), ankle stiffness (1) or did not report which specific joint was assessed (2). The most common methods used to calculate stiffness were the McMahon and Cheng (1990) formula used to determine leg stiffness (7) and/or vertical stiffness (6) and the Farley et al. (1999) (3) formula used to assess joint stiffness. Table 3.6 highlights the data collection methods implemented, variables associated with the underlying mechanisms which contribute to stiffness modulation and performance. Few studies utilised electromyography (8) to assess muscle activation patterns, limited studies employed the use of three dimensional motion analyses (6) as the majority utilised two dimensional video analyses (13).

Of the studies that aimed to assess differences in lower-extremity stiffness and potential control strategies between multiple sub-populations (8), few investigated differences between multiple athletic groups (4) and the remaining assessed differences between an athletic group and control population (4). Furthermore, of these studies the majority recruited male participants (3), the remaining assessed females (1) and several did not report which gender was recruited (4). The majority employed the use of jump tasks (7) (maximal countermovement jump (6) and maximal drop jump (2)) and the remaining assessed differences between populations during a sprinting task (1). Muscle activation patterns were assessed in three studies through the use of electromyography. Finally, applied lower-extremity stiffness measures investigated included leg and joint stiffness (3), joint stiffness (2), leg stiffness (2), vertical stiffness (1). Table 3.7 illustrates the reported key findings and conclusions for each study.

Table 3.5- *Limbs Assessed, Movement Tasks Utilised and Type of Stiffness Evaluated of the Articles Included for Data Extraction.*

Articles	Limb Used	Limb Assessed	Task	No of Trial/s	Stiffness	Formula to Derive Stiffness
Ambegaonkar et al. 2011	Bi-lateral	Preferred leg	Maximal vertical drop jumps (40 cm)	5	k_{leg}(L) k_{joint} (J) (knee)	L- McMahon & Cheng (1990) J- Schmitz & Shultz (2010)
Arampatzis et al. 1999	Uni-lateral	Not reported	Running at varying velocities; 2.5, 3.5, 4.5, 5.5 and 6.5 m/s	NR	k_{vert} (V) k_{leg} (L) k_{joint} (knee and ankle)	L + V- McMahon & Cheng (1990) J- Estimated using two rotational spring (validated NR)
Arampatzis, Brueggemann et al. 2001	Not reported	Not reported	Maximal drop jumps (20 and 40 cm)	4	k_{leg} k_{joint} (knee and ankle)	Linear Regression (validated NR)
Arampatzis, Schade et al. 2001	Not reported	Not reported	Maximal drop jumps (20, 40 and 60 cm)	6-9	k_{leg} k_{joint} (knee and ankle)	Stefanyshyn & Nigg (1998)
Arampatzis et al. 2004	Not reported	Not reported	Maximal drop jumps (40 cm)	6-9	k_{leg} k_{joint} (knee and ankle)	Linear Regression (validated NR)
Boullosa et al. 2011	Not reported	Not reported	Maximal counter movement jump and maximal 20 m sprint	2	k_{vert}	Farley et al. (1993)
Bret et al. 2002	Bi-lateral	Both	100m sprint (race), maximal concentric loaded half squats, maximal countermovement jump and 10 sec maximal hopping test	1 x sprint 2 x squat and hopping tests and 5x CMJ	k_{leg}	Dalleau (1998)
Clark 2009	Bi-lateral	Both	Sprint followed by 3 seconds of hopping (frequency 2.2Hz)	8	k_{joint}	Farley et al. (1990)
Comyns et al. 2007	Uni-lateral	Preferred leg	Drop jumps (30 cm)	NR	k_{vert}	Ferris & Farley (1997)

Articles	Limb Used	Limb Assessed	Task	No of Trial/s	Stiffness	Formula to Derive Stiffness
Dutto et al. 2002	Uni-lateral	Both	Run to exhaustion (approximately 45 mins)	1	k_{leg} k_{vert}	NR
Farley et al. 1996	Uni-lateral	Not reported	10 min treadmill running at 2.5 m/s (26% less and 36% greater preferred stride frequency)	2	k_{leg} (L) k_{vert} (V)	L- McMahon & Cheng (1990) V- McMahon & Cheng (1990)
Girard et al. 2010	Bi-lateral	Not reported	5000 m self-paced run	1	k_{leg} k_{vert}	McMahon & Cheng (1990)
Harrison et al. 2004	Uni-lateral	Dominant leg	Maximal counter movement jump, squat jump and maximal drop jump (30 cm)	5	k_{vert}	McMahon & Cheng (1990)
Hobara, Inoue et al. 2010	Uni-lateral	Right leg	400 m sprint performance	NR	k_{leg} k_{vert}	Morin et al. (2005)
Hobara et al. 2008	Bi-lateral	Not reported	Maximal hopping repeated 15 times (frequency of 1.5 and 3.0 Hz)	5	k_{leg} (L) k_{joint} (J; hip, knee, ankle)	L- Farley & Morgenroth (1999) J- Farley et al. (1998)
Hobara, Kimura et al. 2010	Bi-lateral	Not reported	Maximal hopping repeated 15 times (frequency 2.2 Hz)	5	k_{leg} k_{joint} (hip, knee, ankle)	Farley et al. (1999)
Hobara et al. 2009	Not reported	Not reported	Maximal hopping repeated 15 times	5	k_{leg} k_{joint} (hip, knee, ankle)	Farley et al. (1999)
Hunter et al. 2002	Not reported	Not reported	Maximal drop jumps (30, 60 and 90 cm) and maximal counter movement jump	3	Eccentric lower limb stiffness	Cavagna (1975) and Ferris & Farley (1997)
Hunter et al. 2007	Not reported	Not reported	1 hour high intensity treadmill run (stride frequencies were increased in random order)	1	k_{leg} k_{vert}	McMahon & Cheng (1990)
Kubo et al. 2007	Uni-lateral	Both	Maximal squat jump, maximal drop jump (20 cm) and maximal counter movement jump	1	k_{joint}	Kuitunen et al. (2002)

Articles	Limb Used	Limb Assessed	Task	No of Trial/s	Stiffness	Formula to Derive Stiffness
Kuitunen et al. 2002	Uni-lateral	Right leg	Sprints at maximal, 70, 80, 90% intensity	NR	k_{vert} k_{joint} (knee and ankle)	NR
Kuitunen et al. 2007	Not reported	Not reported	Maximal rebound/drop jumps and submaximal (70% of maximal)	100 maximal rebound, submaximal till exhaustion	k_{leg}	NR
Kulig et al. 2011	Uni-lateral	Preferred leg	Maximal sauté de chat	8	k_{joint} (knee)	NR
Laffaye et al. 2005	Uni-lateral	Not reported	Maximal run and jump task at target heights of 55, 65, 75, 85 and 95% maximal height	5	k_{leg}	Arampatzis et al. (2001)
Morin et al. 2006	Not reported	Not reported	Maximal 100 m sprints	4	k_{leg} k_{vert}	Morin et al. (2005)
Rabita et al. 2008	Bi-lateral	Not reported	Four consecutive maximal jumps	2	k_{leg}	McMahon & Cheng (1990)
Slawinski et al. 2008	Uni-lateral	Not reported	2000 m exhaustive running exercise	1	k_{leg} k_{vert}	McMahon & Cheng (1990)
Song et al. 2010	Bi-lateral	Uni-lateral	Maximal drop jump from (30, 60, 90 cm) then jump over 60 cm barrier	3	k_{joint} (knee and ankle)	Farley & Morgenroth (1999)
Stefanyshyn et al. 1998	Uni-lateral	Not reported	Distance runners- 4 m/s runs and sprinters- maximal sprints (7.1- 8.4 m/s)	D- 10 S- 6	*Kjoint*(ankle)	Least square linear regression (Validated NR)
Toumi et al. 2004	Bi-lateral	Not reported	Maximal squat jump and maximal counter movement jump	3	k_{joint} (knee)	Kuitunen et al. (2002)
Watsford et al. 2010	Uni-lateral	Both	3 consecutive hops (frequency 2.2 Hz)	1	k_{vert} *(reported as* k_{leg}*)*	Farley et al. (1991), Farley et al. (1997)

k_{vert}- Vertical Stiffness, k_{leg}- Leg stiffness, k_{joint}- Joint Stiffness, NR: Not reported.

Table 3.6- *Data Collection Methods, Performance Measures, Joint Contributions and Neuromuscular Assessment of Articles Included for Data Extraction.*

		EQUIPMENT							PERFORMANCE MEASURES														JOINT CONTRIBUTIONS				NEUROMUSCULAR CONTROL			
Articles	**Intervention**	Force Plate	Other Force Devices	Electromyography	3D Video	2D video	Other Motion Analysis	Timing/Velocity System	COM Displacement	Leg Length Change	Ground Contact Time	Flight Time	Total Time	Peak GRF	Time to Peak Force	Peak Power	Velocity (Peak or Changes)	Vertical Velocity Take Off	Time to Max Velocity	Stride Rate/Frequency	Stride Length	Jump Height	Joint Angle Change	Touchdown Angle	Angular Velocity	Joint Moments	Muscle Pre-activation	Muscle Activity	Muscle Co-contraction	Energy Storage
Ambegaonkar et al. 2011		X		X	X																		X			X	X			
Arampatzis, et al. 1999		X				X		X	X	X				X		X										X				
Arampatzis, Brueggemann et al. 2001		X		X		X			X		X			X									X			X	X	X		X
Arampatzis, Schade et al. 2001		X		X		X			X		X			X		X									X					
Arampatzis et al. 2004		X				X			X		X			X		X		X					X			X				X
Boullosa et al. 2011	X	X						X	X					X		X						X								
Bret et al. 2002			X			X								X			X					X								
Clark 2009	X	X											X				X													
Comyns et al. 2007	X	X				X			X			X		X								X								
Dutto et al. 2002			X						X		X			X						X	X									
Farley et al. 1996		X							X		X			X							X									
Girard et al. 2010		X							X	X	X			X			X			X	X									
Harrison et al. 2004		X				X						X				X	X													
Hobara, Inoue et al. 2010			X			X			X	X	X	X		X			X			X	X									
Hobara et al. 2008		X		X		X			X		X	X		X									X	X		X		X	X	
Hobara, Kimura et al. 2010		X				X			X		X	X		X									X	X		X				
Hobara et al. 2009		X				X					X	X		X									X							
Hunter et al. 2002	X	X							X		X											X								
Hunter et al. 2007			X																	X										X
Kubo et al. 2007	X	X		X		X								X									X		X				X	
Kuitunen et al. 2002		X		X		X					X	X		X						X	X					X	X	X		
Kuitunen et al. 2007		X		X							X	X															X	X		

		EQUIPMENT							PERFORMANCE MEASURES														JOINT CONTRIBUTIONS				NEUROMUSCULAR CONTROL			
Articles	**Intervention**	Force Plate	Other Force Devices	Electromyography	3D Video	2D video	Other Motion Analysis	Timing/Velocity System	COM Displacement	Leg Length Change	Ground Contact Time	Flight Time	Total Time	Peak GRF	Time to Peak Force	Peak Power	Velocity (Peak or Changes)	Vertical Velocity Take Off	Time to Max Velocity	Stride Rate/Frequency	Stride Length	Jump Height	Joint Angle Change	Touchdown Angle	Angular Velocity	Joint Moments	Muscle Pre-activation	Muscle Activity	Muscle Co-contraction	Energy Storage
Kulig et al. 2011		X			X						X			X	X								X			X				
Laffaye et al. 2005		X			X				X					X								X								
Morin et al. 2006			X					X	X	X	X	X	X	X			X		X	X										
Rabita et al. 2008		X																				X								
Slawinski et al. 2008		X					X		X		X	X		X			X			X	X									X
Song et al. 2010		X			X						X			X												X				
Stefanyshyn et al. 1998	X			X																			X			X		X		
Toumi et al. 2004	X	X		X	X				X									X				X	X			X		X		
Watsford et al. 2010		X																												
Number of Studies	6	26	5	8	6	13	1	3	17	4	17	10	2	21	1	5	7	2	1	7	6	7	10	2	2	11	4	5	2	4

Table 3.7- *Key Findings and Conclusions of Articles Included for Data Extraction.*

Articles	Key Finding(s)	Conclusion(s)
Ambegaonkar et al. 2011	Dancers: higher $k_{leg.}$ Dancers: no significant differences in k_{knee} during landing phase (limitation: did not account for variations across all lower extremity joints).	Dancers modulate muscles in an ACL protective manner through early activation of medial hamstring. Varying neuromuscular patterns occur due to differing training demands (Dancers practice landing/jumping, Basketball players more reactive). Dancers achieved higher k_{leg} due to training i.e. ballet trains individuals to maintain stiffer ankles.
Arampatzis et al. 1999	No differences for k_{leg} or k_{ankle} for the five given velocities. Running velocity influenced $k_{knee,}$ changes in knee joint angle and maximum moment and mechanical power at the ankle and knee joints.	Running velocity influenced k_{leg}, k_{vert} and F_V. Increased velocity lead to larger changes k_{knee} when compared to k_{ankle} in comparison to the ankle joint. k_{leg} increased due to increased k_{knee}. Increasing velocity altered k_{knee} and k_{leg}, an important variable for efficient running.

Articles	Key Finding(s)	Conclusion(s)
Arampatzis, Brueggemann et al. 2001	k_{leg}, k_{knee} and k_{ankle} increased with shorter contact time. High linearity between F_V and COM_{Vert}, and joint moment and change in joint angle of the ankle and knee during both jump heights. Higher k_{leg} increased energy transmitted to the sprung surface and decreased energy absorption during drop jump. Differences in ankle and knee joints moments and mechanical power. Relationship between k_{leg} and muscle pre-activation. k_{leg} correlated to k_{knee} and k_{ankle}, (highest at the knee joint).	Contact time can control k_{leg} on a sprung surface during drop jumps. k_{leg} positive influence on energy stored and maximal mechanical power. k_{leg} modulated by altered body geometry at touchdown to maximise mechanical power by optimal pre-activation of leg muscles. Optimal k_{leg} is required to maximise mechanical power in positive phase of DJ. k_{leg} aids in improved performance: maximal vertical velocity and maximal energy at take-off. k_{knee} plays an important role in modulating $k_{leg.}$
Arampatzis, Schade et al. 2001	No difference between COM vertical velocities at touchdown. Shorter contact time increased k_{leg} and k_{ankle}. F_V lowest at higher contact times and higher with shorter contact time. Contact time was proportional to COM displacement and influenced joint moment and mechanical power at the ankle and knee joints. Varying jumping conditions influence pre-activation.	Vertical take-off velocity can be maximised through optimal k_{leg}. F_V and vertical path of the COM was determination factor of jump heights, moment and ankle angle change. Optimal k_{leg} can maximise mechanical power during the positive phase of DJ. Contact time regulates $k_{leg.}$ Muscle activation levels altered stiffness.
Arampatzis et al. 2004	No difference in k_{leg}, $k_{knee,}$ $k_{ankle,}$ F_V , COM displacement, peak joint moment and change in angle the knee and ankle between jumps on hard or soft surface. Higher jump height due to increased energy storage on soft surfaces. Softer surfaces had greatest energy loss. Mechanical work similar during upward phase and greater in downward phase for hard surfaces only.	Individual's modulated surface differences by modifying mechanical strategies i.e. lower F_V in soft surfaces. Biological systems are able to adapt k_{leg} to exhibit same k_{leg} scores on surfaces with different stiffness surfaces.

Articles	Key Finding(s)	Conclusion(s)
Boullosa et al. 2011	Increased CMJ height and peak power, and decrease in peak force when fatigued. Sprint performance was maintained under fatigued conditions.	Smaller loss of peak force maintains mean power and peak force. Neuromuscular system in endurance athletes aims to preserve force through peak power enhancement leading to improved jump performance. Athletes demonstrate a muscular fatigue tolerance, speculated to occur as a result of muscular adaptations.
Bret et al. 2002	Maximum force corresponded to heaviest load lifted during loaded squats. Peak force and CMJ jump height related to mean velocity. k_{leg} was not correlated to mean velocity, maximum force or CMJ height. k_{leg} was correlated to velocity changes for different sprint phases.	Athletes with the highest stiffness values exhibited highest acceleration from the first and second phase, however decreased from the second to third phase. k_{leg} was highest during the second phase of 100 m sprint, subsequently increasing the ability of an individual to reach maximal velocity. Leg strength important during sprint performance. High level of k_{leg} contributed to an enhance ability to reach higher velocities in second phase of 100 m sprint.
Clark 2009	Athletic trained group displayed lower sprint times and higher joint stiffness. Sprint times increased for both groups as testing sessions increased. No differences in joint stiffness between dominant and non-dominant limb.	Non-athletes lack neuromuscular adaptations which are developed though training. Non-athletes lacked the ability to modulate stiffness during maximal stretch shortening cycle contractions. Athletes displayed an increased ability to regulate joint stiffness. High-intensity, lower-limb training may enhance an individual's ability to regulate k_{leg}.

Articles	Key Finding(s)	Conclusion(s)
Comyns et al. 2007	Significant reduction in contact time, increase in $k_{vertical}$ and reduction in RSI following lifting of 93% 1-RM loads. Significant reduction in flight time in for all three loads. No significant difference in F_V.	Heavy resistance training may result in a more efficient stretch shortening cycle and subsequent stiffness generation. Heavy resistance training of rugby players contributes to enhanced speed and increased leg cadence. Long-term muscle function and joint adaptations to complex training programs are unclear.
Dutto et al. 2002	Significant changes in stride rate and contact time following run to exhaustion. Significant decreases in $k_{vertical}$ and k_{leg} through the duration of the run. k_{leg} decreased in the first 25% of the run then remained constant. k_{leg} changes were associated with altered leg displacement. $k_{vertical}$ continually declined through the run and was linked to increased COM displacement. Changes $K_{vertical}$ were proportional to changes in stride rate.	Peak F_V maintenance during fatigued running, despite increased time of force application, increased COM displacement and decreased stiffness. Inability to maintain k_{leg} leads to exhaustion when running at constant speed. Runners may continually alter running kinematics during fatigued conditions. Muscles were unable to maintain contraction patterns necessary to maintain leg kinematics. Stiffness optimisation in regard to injury mechanics and performance is unclear.
Farley et al. 1996	Peak F_V occurred at heel strike during ground contact. Significant decrease in contact time and vertical COM displacement occurred at higher stride frequencies. $K_{vertical}$, k_{leg} and slope of the vertical force-displacement increased at higher stride frequencies. Angle swept by the system also decreased.	Subjects adjusted their mechanical behaviour to accommodate for altered stride frequency. Individuals modulate stiffness to become stiffer as stride frequency increases at a given running speed. Muscle activity around the joints of the leg may alter k_{leg}.

Articles	Key Finding(s)	Conclusion(s)
Girard et al. 2010	Running velocity, stride length, stride frequency, F_V and $K_{vertical}$ decreased. k_{leg} remained constant. $K_{vertical}$ was higher in highly trained athletes and resulted in reduced contact time.	No significant interaction was established between fatigue and training status. This suggests training status did not influence mechanical parameters. Inferred that continuous neural adjustments occurred to maintain stiffness.
Harrison et al. 2004	Differences exist between sprint and endurance groups. Sprinters jumped higher in all jump variations. Similar differences were found between groups in all jumps tasks. Sprinters displayed significantly higher k_{leg} scores in CMJ and DJ. Power velocity relationship differed between sprinters and endurance runners.	Endurance athletes appeared to augment performance using a retained pre-stretch (an important variable in sub-maximal performance). Results cannot be compared to running actions as the sledge controlled upper-body movement and allowed for more controlled impact loads
Hobara, Inoue et al. 2010	Peak $K_{vertical}$ occurred in the 50-100 m interval and progressively decreased due to increased COM displacement. Peak k_{leg} occurred between the 0-50 m interval then remained constant from 50 m to finish. k_{leg} change was linked to increased leg length change. Forward velocity and stride length peaked in the 50-100 m and gradually decreased. Contact time progressively increased as a result stride frequency decreased.	$K_{vertical}$ correlated to forward velocity and stride frequency and is necessary for maintaining performance. Higher $K_{vertical}$ is beneficial for better energy absorption/generation during contact. k_{leg} remained constant and unrelated to forward velocity, stride frequency or length. Vertical component of the leg spring is a major determinant of running performance. Altered lower limb kinematics increased stiffness.

Articles	Key Finding(s)	Conclusion(s)
Hobara et al. 2008	At 1.5 Hz power athletes displayed shorter contact time and longer flight time. Power athletes higher k_{leg}]at both frequencies. k_{ankle} greater at 3.0 Hz and k_{knee} joint at the 1.5 Hz. Differences in k_{ankle} (3.0 Hz) and k_{knee} (1.5 Hz). Peak EMG activity of the rectus femoris, vastus lateralis, medial gastrocnemius and soleus occurred prior to landing.	Between group differences in joint stiffness attributed to intrinsic properties of the musculoskeletal system. Muscle activity larger in the endurance group. Power trained athletes have stiffer leg springs when compared to endurance runner due to increased k_{joint} as a result of intrinsic stiffness.
Hobara, Kimura et al. 2010	Endurance athletes: higher k_{leg}, k_{knee}, k_{ankle} and flight time; lower contact time. Hip stiffness and touchdown angle did not differ.	Higher k_{leg} due to intrinsic differences of the tendonous tissue, muscle and muscle fibres through training. Increased understanding of the influence of training on k_{leg} may provide a better basis for evaluating injury prevention. Findings indicate runners were at higher risk of overuse injuries.
Hobara et al. 2009	k_{knee} and moment was higher than k_{hip} and k_{ankle} and moment. k_{knee} joint correlated to k_{leg}. Higher range of motion at the knee joint affected jump and running performance.	Knee joint is essential for regulating performance. Elastic behaviour of knee extensors plays a major in power generation. Higher K_{knee} occurred due to greater knee moment and angular displacements when compared to ankle and hip joints. Increased insight on stiffness regulation can assist in sports performance evaluation.

Articles	Key Finding(s)	Conclusion(s)
Hunter et al. 2002	Training and DJ lead to lower k_{leg}, greater CMJ depth and longer contact time. Optimal k_{leg} was achieved when jump height was achieved. Power training independent of stretching was shown to increase k_{leg} during CMJ, but decreased during all DJ conditions. Power training resulted in greater vertical COM displacement. Contact time increased with DJ height.	Stretching has little effect on jump technique variables, however may have performance outcome benefits for CMJ. No evidence that stretching influenced COM displacement and contact time. Power training decreased DJ k_{leg} needed to absorb early F_V and improve jump height.
Hunter et al. 2007	No significant decrease in k_{leg} or $K_{vertical}$. Significant decrease in stride frequency. Running speed weakly correlated to $K_{vertical,}$ k_{leg} and stride frequency. Increased stiffness and frequency resulted in improved economy.	Subjects self-optimised their stride frequency. Higher stride frequencies lead to higher levels of stiffness. Runners adjusted the frequency-stiffness characteristics to minimise metabolic cost. Optimisation of stride frequency can be achieved through a balanced ratio of elastic energy storage vs the cost required to accelerate the limbs. Future studies should aim to understand control mechanisms.

Articles	Key Finding(s)	Conclusion(s)
Kubo et al. 2007	Muscle co-activation level was not influenced by plyometric and/or weight training. Power training reduced time to peak torque and increased elastic energy. No difference in ankle angle at the lowest position during all jump tasks. Plyometric training altered angular velocity in the concentric phase of squat jumps. Plyometric training increased CMJ and DJ jump height. Both training types increased EMG of plantar flexors in all jumps. k_{ankle} increased following plyometric training. No change following weight training.	Increase in jump heights was greater for power training than weight training. Plyometric training changed muscle tendon properties increasing suitable for stretch shortening cycle exercises. Increases in k_{ankle} following plyometric training lead to changes in the mechanical properties of muscle-tendon complex and improved jump performance.
Kuitunen et al. 2002	Stride frequency was linked to higher running speed and changes in stride length. Increased running speed lead to decreased contact time, flight time, COM displacement and increased peak vertical and anterior/posterior force. As speed increased peak ankle joint moments remained constant, decreased at the knee joint and increased in the hip joint. $K_{vertical}$ increased, k_{knee} increased and k_{ankle} remained constant. Increase in k_{knee} was most prominent at 90% of maximal speed. No correlations between k_{ankle} and k_{knee} and increased running speed.	Linear relationship between $K_{vertical}$ and running speed, due to decreased vertical COM displacement. Higher k_{ankle} lead to shorter contact time. Did not change with higher running speed. Contact time decreased, due to mechanical properties of the muscle-tendon unit and neural activation patterns. During sprinting the leg adjusts by modulating k_{knee} while k_{ankle} remains constant. Stiffness increased due to increased pre-activation of plantarflexors and knee extensors. Allowing for increased to tolerance and absorption of high impact loads at the knee during contact.

Articles	Key Finding(s)	Conclusion(s)
Kuitunen et al. 2007	No change in k_{leg}, peak F_V , contact time or EMG during DJ. Decreased k_{leg}, peak F_V, muscle activation and increased contact time occurred in sub maximal jumping. Decreased soleus and Gastrocnemius EMG activity during the sub-maximal jumping due to peak F_V reduction.	k_{leg} attenuation contributed to time to exhaustion in fatiguing stretch shortening cycle exercise. EMG ratio may be a useful indicator for assessing k_{leg} modulation. Inefficient muscle activation was linked to metabolic fatigue. Subjects with higher EMG ratios took longer to reach exhaustion. Research should assess k_{leg} and EMG ratios as it may reduce performance declines.
Kulig et al. 2011	Peak F_V was greater during landing than take off. Peak F_V occurred earlier in the landing phase. Knee angular displacement was higher in the weight acceptance phase of landing. No difference between peak knee flexor moments. k_{ankle} during landing was only 67 % of that displayed during take-off. Increased knee extension at touchdown allowed for increased joint angular displacement. Peak flexion occurred later in landing.	Dancers achieved greater peak F_V with less k_{ankle}. Through training dancers modify stiffness to achieve a hard landing (high stiffness and force) and soft landing (low stiffness and force). Aesthetic demands of dance training can prevent dancers from displaying increased hip flexion; however display greater knee flexion of the knee which may contribute to high prevalence of knee injuries. Dancers optimise take-off by increasing angular stiffness, to achieve greater leap height and decrease k_{ankle} during landing to avoid injury occurrence.

Articles	Key Finding(s)	Conclusion(s)
Laffaye et al. 2005	Differences exist between the four expert jumpers and novices. Relative force was higher in Fosbury athletes and lower in volleyball players. Higher values of relative force occurred as jump height increased. Contact time decreased as height increased. Increasing the compression of the spring occurred as target height increased. Negative loading of both force and stiffness exhibited a relationship between contact time and increase in k_{leg} through ground reaction force. Experts jumped higher than the novices.	Volleyball players displayed long impulse, lower k_{leg} and $F_{V.}$ Fosbury athletes maximised performance through increased angle swept by the leg. Experts compressed the of leg spring to achieve great jump height. Task demands of the run and jump task accounted for the increased F_V, leg compression and decreased k_{leg} associated with jump height. Training may result in a motor control signature relative to each specific sport, however requires further investigation. Novices displayed non-adaptive utilisation and exhibited unpredictable changes.
Morin et al. 2006	Initial 100 m sprint showed declines in mean forward velocity. No correlation between any mechanical parameter and sprint performance. Increase in contact time, COM displacement and velocity loss occurred during sprint repetitions. Declines in $K_{vertical}$, mean forward velocity, stride frequency, mean velocity, time constant acceleration and deceleration and were evident. Changes in $K_{vertical}$ linked to changes in COM displacement and stride frequency. k_{leg} remained constant.	Larger declines in $K_{vertical}$ in sprint repetition were associated with larger declines in mean and maximal velocities. A positive relationship between $K_{vertical}$ and both mean 100 m velocity and mean forward velocity. Subjects who limited their increase in COM displacement during contact achieved higher velocities thought the 100 m repetitions.
Rabita et al. 2008	Athletic group showed significantly higher k_{leg} (51.8%) and hopping height (26%). $K_{vertical}$ of vertical hopping performance was inversely correlated in jumpers.	Differences occurred due to varying neuromuscular control, although EMG was not collected.

Articles	Key Finding(s)	Conclusion(s)
Slawinski et al. 2008	All assessed mechanical parameters remained constant. Exhaustive 2000 m run showed no differences in k_{leg}, $K_{vertical}$, F_V or F_H. k_{leg} was correlated to energy cost. $K_{vertical}$ was not correlated to energy cost.	Subjects made mechanical modifications towards the end of the exercise in order to maintain intensity and performance. Decrease in energy cost can lead to improved endurance running performance. Stiffness is associated to two training types: technical interval and plyometric training.
Song et al. 2010	No interaction between DJ heights and legs for all outcome variables, except for knee flexion angle at touchdown. k_{knee} and k_{ankle} was significantly lower as DJ height increased. Joint moments were higher in 60 DJ and 90 DJ when compared to 30 DJ. Larger knee and ankle joint angle changes during contact as DJ height increased.	DJ height increased knee and ankle joint became more extend and plantar-flexed. High-level athlete's decreased k_{knee} and k_{ankle} as DJ height increased. Adjustments of k_{knee} and k_{ankle} as DJ height increased were attenuated through knee and ankle angles during touchdown. Tendon and muscle stiffness increased with the force and muscle activation level.

Articles	Key Finding(s)	Conclusion(s)
Stefanyshyn et al. 1998	During both running and sprinting subjects exhibited dorsiflexion at touchdown through to mid-stance phase while continually increasing plantar flexor moments. Ankle joint moment produced extensor moment for both running and sprinting. Allowing the ankle joint to absorb energy in the first half of the stance while the ankle is dorsiflexed. Energy was generated as the ankle was plantar flexed. k_{ankle} was significantly higher during running. k_{ankle} remained constant though the entire range of motion and corresponded to the resultant joint moments.	k_{ankle} is a specific characteristic of the activity or demand which is placed upon the ankle. Sprinters require higher joint moments as the ankle undergoes approximately the same range of flexion-extension and still accelerates through the movement while runners maintain a constant speed. k_{ankle} plays an important role in performance.
Toumi et al. 2004	Both training types increased squat jump performance. Combined training decreased the CMJ duration in the eccentric and transition phase and increased muscle activity of knee extensor's. k_{knee} increased in the CMJ eccentric phase.	Both training types improved maximum power output during concentric movements due to changes in neural drive and muscle activity. Changes from combined training are attributed to increased functional capacity of activated muscles to store and return elastic energy. Altered jump technique allowed for shorter transition phases, increased k_{knee} and muscle activation patterns translating to the concentric phase.

Articles	Key Finding(s)	Conclusion(s)
Watsford et al. 2010	Injured limb showed significantly higher k_{leg} values. No difference in k_{leg} between limbs in the non-injured group. High relationship between injury incidence and stiffness (11% higher bi-lateral k_{leg}).	Players who sustained an injury were significantly older and recorded a significantly higher bilateral mean k_{leg} values. High bi-lateral k_{leg} difference linked with increased risk of soft tissue injury Increased neural drive may increase injury risk. Stiffness magnitude is the pertinent marker for injury risk

CMJ- Countermovement jump; COM- Centre of mass; DJ- Drop jump; EMG- Electromyography; F_V- Peak vertical ground reaction force; F_H – Peak horizontal ground reaction force; $k_{vericalt}$- Vertical Stiffness; k_{leg}- Leg stiffness, k_{hip}- Hip Joint Stiffness; k_{knee}- Knee Joint Stiffness; k_{ankle}- Ankle Joint Stiffness; RSI- Reactive strength index.

Results for the STROBE criteria are displayed in Tables 3.8 and 3.9, which established that three clear areas of reporting were lacking. Firstly, only 6.5% (2 of 31) of the articles explicitly indicated the studies design in the title or abstract, secondly 6.5% (2 of 31) of the articles stated how the participant sample size was determined and thirdly 33.3% (9 of 27) of cross-sectional articles provided a clear inclusion and exclusion criteria for participants. In general, most studies effectively reported data collection methods, statistical methods employed, results and insightful discussion of data. Total STROBE scores for each article (Table 3.9) ranged from 59.9% to 87.0%, with the highest scoring articles being Ambegaonkar et al. (2011) (86.4%) and Hobara et al. (2010) (87%), while the lowest scoring articles were Arampatzis et al. (2001) (59.5%) and Arampatzis et al. (1999) (61.9%). Interestingly, recently published articles scored higher in STROBE, while older articles tended to score the lowest, suggesting the quality of reporting has evolved over time.

Table 3.8- *Strengthening the Reporting of Observation Studies in Epidemiology (STROBE) Criteria and Percentage Score for Each Criterion of Included Articles.*

	Criteria	Sum	Out Of	Percentage of Papers That Meet The Criteria
Title and Abstract	1 (a)	2	31	**6.5 %**
	1 (b)	31	31	**100.0 %**
Introduction				
Background/ Rational	2	30	31	**96.8 %**
Objectives	3	31	31	**100.0 %**
Methods				
Study Design	4	28	31	**90.3 %**
Setting	5	16	31	**51.6 %**
Participants	6 (a-i)	3	3	**100 %**
	6 (a-ii)	0	1	**0.0 %**
	6 (a-iii)	9	27	**33.3 %**
	6 (b-i)	NA	NA	**NA**
	6 (b-ii)	NA	NA	**NA**
Variables	7	25.5	31	**82.3 %**
Data sources/ Measurement	8	31	31	**100.0 %**
Bias	9	10	31	**32.3 %**
Study Size	10	2	31	**6.5 %**
Quantitative Variables	11	13	31	**41.9 %**
Statistical Methods	12 (a)	29	31	**93.5 %**
	12 (b)	13	13	**100.0 %**
	12 (c)	3	3	**100.0 %**
	12 (d-i)	NA	NA	**NA**
	12 (d-ii)	NA	NA	**NA**
	12 (d-iii)	NA	NA	**NA**
	12 (e)	NA	NA	**NA**
Results				
Participants	13 (a)	11	11	**100.0 %**
	13 (b)	1	1	**100.0 %**
	13 (c)	NA	NA	**NA**
Descriptive Data	14 (a)	20	31	**64.5 %**
	14 (b)	1	1	**100.0 %**
	14 (c)	3	3	**100.0 %**
Outcome Data	15 (i)	3	3	**100.0 %**
	15 (ii)	1	1	**100.0 %**
	15 (iii)	27	27	**100.0 %**
Main Results	16 (a)	29	31	**93.5 %**
	16 (b)	NA	NA	**NA**
	16 (c)	NA	NA	**NA**
Other Analyses	17	13	13	**100.0 %**

	Criteria	Sum	Out Of	Percentage of Papers That Meet The Criteria
Discussion				
Key Results	18	31	31	**100.0 %**
Limitations	19	23	31	**74.2 %**
Interpretation	20	31	31	**100.0%**
Generalisability	21	30	31	**96.8 %**
Other Information				
Funding	22	10	10	**100.0 %**

See Appendix A for a breakdown of strengthening the reporting of observation studies in epidemiology (STROBE) criteria.

Table 3.9- *Overall percentage STROBE score of each article.*

Articles	Overall STROBE Score
Ambegaonkar et al. 2011	86.4 %
Arampatzis et al. 2001	59.5 %
Arampatzis et al. 1999	61.9 %
Arampatzis et al. 2001	71.4 %
Arampatzis et al. 2004	64.3 %
Boullosa et al. 2011	77.5 %
Bret et al. 2002	82.6 %
Clark 2009	75.0 %
Comyns et al. 2007	80.0 %
Dutto et al. 2002	69.0 %
Farley et al. 1996	66.7 %
Girard et al. 2010	62.5 %
Harrison et al. 2004	81.8 %
Hobara, Inoue et al. 2010	70.0 %
Hobara et al. 2008	82.6 %
Hobara, Kimura et al. 2010	87.0 %
Hobara et al. 2009	66.7 %
Hunter et al. 2002	85.7 %
Hunter et al. 2007	76.2 %
Kubo et al. 2007	82.6 %
Kuitunen et al. 2002	80.4 %
Kuitunen et al. 2007	69.0 %
Kulig et al. 2011	82.5 %
Laffaye et al. 2005	78.3 %
Morin et al. 2006	75.0 %
Rabita et al. 2008	73.9 %
Slawinskie et al. 2008	76.2 %
Stefanyshyn et al. 1998	73.9 %
Song et al. 2010	67.5 %
Toumi et al. 2004	82.6 %
Watsford et al. 2010	85.4 %

Note: Higher percentage scores represent a higher quality of reporting, lower scores represent a lower level of reporting not the overall quality of the research.

3.4 Discussion

3.4.1 Main Objective and Relevance of the Study

The objective of this study was to evaluate the existing knowledge of vertical, leg and joint stiffness in relation to training development and athletic practice in adult populations. The present study also subsequently sought to evaluate the methods used to quantify lower-extremity stiffness in athletes. Limited research has profiled and examined the between-population differences in functional stiffness of the lower-extremity in diverse athletic training backgrounds. Furthermore, the muscular and neural control strategies utilised by different athletic populations to attenuate functional lower-extremity stiffness in order to meet task demands remain unknown. The present review offers an assessment of the current literature investigating the influence of athletic training on functional lower-extremity stiffness, and highlights gaps within the literature and areas for further research.

3.4.2 Quality of Reporting

The implemented customised STROBE criteria (Von Elm et al., 2007) highlighted areas of reporting which required improvement within the existing literature relevant to functional lower-extremity stiffness and athletic training.

3.4.2.1 Sample Size and Participant Characteristics

The quantification of sample size and criteria for participant inclusion was found to be under-reported. Recruiting an adequate group sample size is important to ensure appropriate conclusions are drawn regarding the acceptance or rejection of the null hypothesis. Power analysis is a useful tool in determining appropriate group sample size (Peat & Barton, 2006). Nevertheless, the variability and inconsistencies regarding participant numbers within the literature highlighted that no consistent or predictable sample size existed for stiffness studies. Only a small percentage (6.5%) of assessed studies (Comyns et al., 2007; Hunter & Marshall, 2002) reported on how the recruited sample size was determined. Therefore, to ensure the appropriateness of researchers' conclusions and findings, it is essential to undertake and explicitly state the methods and analysis used to determine the appropriate sample size.

When investigating the participant characteristics (age, gender, weight, height and training age/skill level), of the applicable cross-sectional articles, 64.5% reported the necessary characteristics. Only 33.3% of the reviewed literature stated clear participant inclusion/exclusion criteria. Several studies did not report the gender assessed (Arampatzis et al., 1999; Arampatzis, Schade, et al., 2001; Clark, 2009; Girard et al., 2010; Hobara et al., 2008; Hobara, Kimura, et al., 2010; Rabita et al., 2008; Watsford et al., 2010). Furthermore, other studies pooled gender data (Boullosa et al., 2011; Dutto & Smith, 2002; Hunter & Smith, 2007; Kulig et al., 2011; Slawinski et al., 2008) despite between-gender differences evident in stiffness modulation, with females displaying an impaired ability to regulate stiffness and subsequent potential increased injury risk (Granata et al., 2002; Padua et al., 2006). The majority of the research has investigated the male population, despite the fact females are at a greater risk of injury. Reporting inconsistencies questions the validity of the results and conclusions drawn from the assessed studies. It is essential that researchers report experimental design criteria, participant characteristics and inclusion criteria to ensure validity, accuracy and repeatability of the study.

3.4.2.2 Bias

An additional area requiring improvement in the quality of research reporting is the description of the strategies implemented to address potential sources of bias within the study. Only 32.3% of the articles assessed identified the methods used to control this issue. Future research should address this key variable to ensure that confounding aspects do not influence the interpretation and accuracy of results thus ensuring data validity is maintained.

3.4.2.3 Overview of Reporting Within the Literature

Overall, when studies were assessed individually, the majority established a high level in the quality of reporting within the assessed literature. Upon more detailed examination and referencing of the STROBE criteria, the more recent studies tended to achieve higher quality of reporting scores (Ambegaonkar et al., 2011; Hobara, Kimura, et al., 2010) than earlier studies that scored lower (Arampatzis, Brueggemann, et al., 2001; Arampatzis et al., 1999). The apparent increase in reporting quality suggests an evolution of higher quality reporting standards over the years to meet current scientific standards.

3.4.3 Athletic Populations Investigated

Populations recruited between studies contained notable limitations. Sprinting and/or endurance athletes were the most common athletic populations investigated (Boullosa et al., 2011; Bret et al., 2002; Harrison et al., 2004; Hobara, Inoue, et al., 2010; Hobara et al., 2008; Hobara, Kimura, et al., 2010; Kuitunen, Komi, et al., 2002; Song et al., 2010; Stefanyshyn & Nigg, 1998) while generic populations such as 'runners' and 'athletes' were also commonly reported (Arampatzis, Brueggemann, et al., 2001; Dutto & Smith, 2002; Hobara et al., 2009; Kuitunen et al., 2007; Rabita et al., 2008). The existence of differences in stiffness profiles between power athletes such as sprinters, endurance runners and sedentary populations is well documented (Hobara et al., 2008; Hobara, Kimura, et al., 2010), however the joint control strategies these athletic populations utilise to modulate stiffness remains unclear. This is of particular concern in female athletes who are under-reported in stiffness literature and tend to be at an increased risk of injury when compared to their male counterparts (Padua et al., 2006).

Task demands and muscle adaptations varied between populations (Girard et al., 2010; Hobara, Inoue, et al., 2010; Kulig et al., 2011), however few studies have accounted for variations in the training requirements, which in turn, may influence functional lower-extremity stiffness attenuation strategies. The majority of the previous findings are specific to sprinting and endurance populations, and as a result, practitioners need to exercise caution when applying findings to other athletic demographics (Boullosa et al., 2011; Bret et al., 2002; Harrison et al., 2004; Hobara, Inoue, et al., 2010; Hobara et al., 2008; Hobara, Kimura, et al., 2010; Kuitunen, Komi, et al., 2002; Song et al., 2010; Stefanyshyn & Nigg, 1998). There appears to be limited knowledge regarding the influence of athletic training on functional lower-extremity stiffness in diverse athletic populations, highlighting the need for further investigation regarding the impact of chronic athletic training on stiffness, performance and injury risk.

Plyometric training can increase lower-extremity stiffness and subsequently allow participants to gain associated performance benefits such as improved jump height (Comyns et al., 2007; Hunter & Marshall, 2002; Toumi et al., 2004). These results suggest that functional lower-extremity stiffness is trainable, however the number of studies that have investigated between-population differences are limited. Of these studies, only four have assessed between-population differences in multiple athletic groups (Ambegaonkar et al., 2011; Harrison et al., 2004; Hobara et al., 2008; Stefanyshyn & Nigg, 1998), while four others have investigated the population differences between athletic and control populations (Hobara, Kimura, et al., 2010; Laffaye et al., 2005; Rabita et al., 2008). There is a need for further research to evaluate lower limb stiffness differences among multiple athletic groups, particularly for the under reported populations such as high-intensity intermittent training populations.

3.4.4 Tasks Used To Assess Lower-Extremity Stiffness

In the examined literature, maximal countermovement and maximal drop jumps were the main tasks used to assess how populations modulate lower-extremity stiffness to meet task demands. It has been established that participants modulate stiffness to meet task demands by using altered joint kinematics and contact times (Arampatzis, Brueggemann, et al., 2001; Arampatzis et al., 1999;

Bret et al., 2002; Butler et al., 2003). Furthermore, some studies have highlighted the performance benefits of higher lower-extremity stiffness achieved through plyometric jump training (maximal rebound jumps) thus allowing participants to increase their maximum jump height (Clark, 2009; Hunter & Marshall, 2002; Kubo et al., 2007; Toumi et al., 2004). Furthermore, there is a known correlation between lower-extremity stiffness and injury risk upon landing from maximal countermovement and drop jumps (Ambegaonkar et al., 2011; Hobara, Kimura, et al., 2010; Kulig et al., 2011; Watsford et al., 2010). However, findings are difficult to translate into practical applications for coaches and athletes as very few sports utilise movement patterns which aim to achieve maximal vertical jump height. There is a need to assess lower-extremity stiffness and the associated stiffness modulation strategies during functional tasks relevant to an athlete's training background, particularly tasks applicable to match play.

Regulation of stiffness is task dependent, whereby stiffness attenuation is reliant upon the relationship between task requirements and the individuals training status (Komi, 2000). Training allows for muscle adaptations that enable athletes to anticipate task demands and adapt according to environmental/situational needs (Girard et al., 2010; Hobara, Inoue, et al., 2010; Hobara et al., 2008; Hobara, Kimura, et al., 2010; Komi, 2000; Kubo et al., 2007; Kulig et al., 2011). However, tasks relevant to an athlete's training background are under-reported within the literature examined as the focus has primarily centred around the relationship between stiffness and jumping movements. Therefore, there is a need to understand the role of stiffness during functional tasks and movement patterns relevant to an athlete's training background along with the development with training over time. Questions still remain regarding an athlete's ability to attenuate stiffness to meet task demands as a result of chronic athletic training and the role of stiffness in performance and injury risk during sports-specific tasks.

Only limited studies have investigated tasks commonly performed within their target population (Girard et al., 2010; Hobara, Inoue, et al., 2010; Kulig et al., 2011). Thus the practical application of findings for coaches and/or athletes may be limited in the research to date. Of these few studies which have investigated sport specific tasks, it was established that athletes modulate stiffness efficiently in order to meet the demands of the movement. Response to task demands was studied in various populations including dancers, endurance runners and track running specialists. Dancer's modified lower extremity stiffness via training adaptations by anticipating task requirements and adapting accordingly (Kulig et al., 2011). For hard stiff landings where minimal flexion at the joints is evident dancers displayed higher stiffness and peak forces while dancers exhibited lower stiffness and lower peak forces during soft landings where dancers absorb the ground contact typically through increased compression at the joints (Kulig et al., 2011). While endurance athletes are able to maintain leg stiffness through the entire duration of an exhaustive run, it is speculated to occur as a result of continuous neural adjustments developed through training adaptations (Girard et al., 2010). Finally, spring mass characteristics were evaluated during a 400 m sprint performance, where declines in vertical stiffness occurred progressively from 100 m (Hobara, Inoue, et al., 2010). However, the majority of participants in this study were 100 - 110 m sprint or endurance specialists and were not accustomed to the demands of 400 m sprints and as a result may have been limited in their ability to anticipate task demands and adapt accordingly. It appears that lower-extremity stiffness and the underlying mechanisms which contribute to stiffness modulation is task and population dependent. There is a need to investigate how athletes modulate lower-extremity stiffness in tasks relevant to an athlete's specific training background to provide further insight and strengthen existing knowledge regarding the influence of chronic athletic training on stiffness, performance and injury.

3.4.5 Assessment of Lower-Extremity Stiffness

The majority of functional stiffness studies have focused on the assessment of stiffness of the leg spring (leg or vertical stiffness), with limited studies assessing stiffness at the joint level. Of the studies which have evaluated joint stiffness measures, research has primary focused on the assessment of ankle and knee joint. Currently, only one study applied a combination of all three functional measures of lower-extremity stiffness (vertical, leg and joint stiffness) to the same task (Arampatzis et al., 1999), and no study compared all functional measures of lower-extremity stiffness between multiple athletic groups. The evaluation of stiffness as a whole unit supplemented by assessment of stiffness at the joint level has the potential to provide a clearer profile of how varying athletic populations regulate lower-extremity stiffness and the potential changes that occur as a result of training over time, as the behaviour at the joint influences the outcome of the entire unit (Ambegaonkar et al., 2011; Hobara et al., 2008; Hobara et al., 2009).

Stiffness measures can be determined through a variety of quantification methodologies based on the standard spring-mass model (Brughelli & Cronin, 2008a, 2008b; Butler et al., 2003). The results of this study established that leg and vertical stiffness measures were predominately calculated using the methods of McMahon and Cheng (1990). The McMahon and Cheng (1990) model is preferred as it refers to dimensional stiffness that enables researchers to validly compare individuals of various body sizes (Butler et al., 2003; McMahon & Cheng, 1990). These calculations are the simplest means of determining specific stiffness as they only require two mechanical parameters; peak vertical ground reaction force and vertical centre of mass displacement for vertical stiffness, and peak vertical ground reaction force and leg length change for leg stiffness measures. However, this method of quantifying lower-extremity stiffness may actually underestimate the leg stiffness measure (Blum, Lipfert, & Seyfarth, 2009) by overestimating centre of mass displacement (Arampatzis et al., 1999). Although other models have proposed alternative methods of determining leg and vertical stiffness (Arampatzis et al., 1999; Dalleau et al., 2004; Morin et al., 2005), researchers still prefer to implement the traditionally accepted McMahon and Cheng formulas as they allow for the comparison between previous studies (Butler et al., 2003).

Understanding muscle activation and neural control strategies implemented by various athletic populations is important as it allows researchers to understand how individuals modulate lower-extremity stiffness. Only eight studies have used electromyography during stiffness assessment (See Table 3.6). Of these studies, only three made comparisons between multiple athletic populations (Ambegaonkar et al., 2011; Hobara et al., 2008; Toumi et al., 2004). A significant reduction in co-contraction around the ankle joint has been associated with an increase in hopping frequency, suggesting that individuals rely on reciprocal inhibition as a means of increasing stiffness (Hobara et al., 2008). It is also known that feed forward mechanisms and proprioceptive feedback play decisive roles in stiffness regulation (Oliver & Smith, 2010). These mechanisms can be inferred through the assessment of muscle pre-activation and co-contraction (Hobara et al., 2008; Kubo et al., 2007). However, the control strategies and muscle patterns employed by athletic populations are typically under-reported within the included literature. Under-reporting was particularly evident when considering muscle co-contraction, which was assessed by only two studies. It appears co-contraction plays an important role in the modulation of functional lower-extremity stiffness (Hobara et al., 2008; Kubo et al., 2007). In diverse athletic populations it is unclear how athletes modulation stiffness and adapt these underlying contributory mechanisms as result of chronic athletic training. It is important that researchers understand the fundamental mechanisms that populations employ to modulate stiffness as it allows further understanding of potential performance benefits and injury risks, thus improving the relevance and practical applications of the research.

It is also essential for researchers to understand and assess the movement kinematics and kinetics used to attenuate lower-extremity stiffness and the subsequent loads experienced during locomotion. Mechanical parameters such as segment velocity, contact time, touchdown angle, joint angle changes and joint moments play an essential role in modulating stiffness to meet performance demands (Arampatzis, Brueggemann, et al., 2001; Arampatzis et al., 1999; Bret et al., 2002; Butler et al., 2003). The requirements of the task impact upon the movement strategies employed in order to achieve the desired outcome of a task i.e. greater degree of joint flexion enable larger jump heights (Komi, 2000; Kulig et al., 2011; Nicol, Avela, & Komi, 2006b). This further emphasises the need to assess the response to tasks specific to an athlete's training background. Although these parameters play an important role during movement and ultimately influence lower-extremity stiffness outcomes, few studies choose to complement their data with comparisons and assessment of the interaction of these variables. Additionally, few studies have implemented the use of three dimensional motion analyses to track segmental interaction of the joints. Three-dimensional analysis allows for a more comprehensive and global view of segments when compared to two-dimensional analysis (Winter, 2005), which is the most common method implemented.

3.4.6 Future Direction

Research has focused on cross-sectional evaluation of the impact of athletic training on lower-extremity stiffness, with the only longitudinal evaluations of lower-extremity stiffness in intervention studies, predominately plyometric training (Hunter & Marshall, 2002; Kubo et al., 2007; Toumi et al., 2004). The present systematic review of the relevant literature establishes the need for longitudinal assessment of the impact of training on lower-extremity stiffness and subsequent performance benefits and associated injury risk.

The relevance of existing knowledge and its practical application for coaches and athletes is limited due to the lack of information based on the assessment of functional tasks and evaluation of diverse athletic populations. The majority of research is based on the assessment of sprinting and endurance populations during maximal vertical jumping tasks (Boullosa et al., 2011; Bret et al., 2002; Harrison et al., 2004; Hobara et al., 2008; Hobara, Kimura, et al., 2010); however movement patterns displayed by these athletic populations rarely require them to jump with the intention of achieving maximal heights. This not only limits the assessed studies practical applications, but also questions the ability of participants to meet task demands if the means of assessment is not specific to their individual training background (Komi, 2000; Nicol et al., 2006b). In addition, due to the absence of literature implementing the use of three dimensional motion analyses and electromyography, the understanding of the role which the underlying mechanisms; such as movement kinematics and muscle activation; play in the attenuation of lower-extremity stiffness is unknown. Assessment of movement kinematics and muscle activation can provide a more detailed profile of the influence of the mechanical parameters such as joint moment, joint angle change, contact time and muscle co-contraction on attenuation of lower-extremity stiffness.

When assessing functional lower-extremity stiffness it is important to gain a comprehensive view of all measures of functional stiffness (Butler et al., 2003). It is known that behaviour at the joint level impacts the overall performance of the entire unit (Ambegaonkar et al., 2011; Hobara et al., 2008; Hobara et al., 2009). However, few studies have evaluated the interaction of all measures of functional stiffness and the attenuation strategies diverse athletic populations employ. It is important to note that although females are known to be at greater risk of injury due to a diminished ability to regulate impact loads, the vast majority of literature has focused on attenuation strategies of male populations (Granata et al., 2002; Padua et al., 2006).

The results of this study suggest that an opportunity exists for researchers to investigate the longitudinal impact of training in diverse athletic populations and the subsequent performance benefits and injury risk athletes are exposed to; particularly in female populations. Additionally, research needs to be undertaken to profile differences between diverse athletic populations and the strategies they employ to meet task demands particularly during functional/task specific movement patterns.

3.5 Conclusions

This systematic review has analysed the research that has been undertaken to date in regard to vertical, leg and joint stiffness in the lower-extremity focusing specifically on training development and athletic practice, including the use of training intervention protocols in adult populations. It is clear research has primarily focused on the assessment of control, recreational, endurance and sprint populations during discrete maximal effort jumping tasks. Therefore, there is sufficient justification to investigate lower-extremity stiffness of diverse athletic populations in tasks reflective of training and competition demands. Although there are known links between stiffness, performance and injury, there is limited understanding of the longitudinal implications of athletic training on lower-extremity stiffness and the underlying stiffness modulation strategies athletes utilise to modify stiffness in tasks relevant to an athlete's training background. Research should aim to quantify profiles of functional lower-extremity stiffness in diverse athletic populations in order to provide relevant information to practitioners, athletes and coaches on ways to enhance performance and appropriate monitoring tools to utilise for early identification of injury risk.

A Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) was conducted to review the quality of reporting of the systematic review (Appendix B). It is important to note a meta-analysis was not undertaken in this systematic review as common methodology was not utilised between studies.

3.6 Summary and Key Findings

Findings of the systematic review indicate a primary focus on the cross sectional assessment of recreational, non-active control and sprint populations during basic jumping tasks in males. Few studies have assessed joint stiffness and the underlying control mechanisms which contribute to leg stiffness. Limited research has also evaluated leg stiffness, joint stiffness and the contributory stiffness control mechanisms in tasks relevant to an athlete's habitual training background. Although there are known links between performance and injury, there is a limited understanding of the longitudinal implications of athletic training on leg stiffness particularly in female demographics who are at increased risk of injury when compared to their male counterparts. Additionally, there is a need to establish appropriate screening and monitoring tools for athletes in order to gain maximal performance benefits and minimise injury risk.

3.7 Recommendations for Future Research

The systematic review established a need to investigate the longitudinal influence of varied athletic training backgrounds on leg stiffness, joint stiffness and the contributory stiffness control mechanisms. To achieve this, four key aims where developed:

1- To investigate differences in leg and joint stiffness between athletes from varied training backgrounds during discrete jumping tasks traditionally utilised to assess stiffness. Further, to evaluate the kinematic and kinetic mechanisms athletic populations utilise to modulate stiffness. *(Focus of Chapter 5)*

2- To investigate differences in leg stiffness in different female sub-populations from varied training backgrounds during dynamic and sports-specific tasks. Further, to evaluate the performance variables which contribute to leg stiffness. Additionally, to assess the relationship between stiffness during dynamic jumping and sports-specific tasks. *(Focus of Chapter 6)*

3- To evaluate differences in leg and joint stiffness in female athletes from different training backgrounds during functional task. Further, to investigate the kinematic and kinetic mechanisms that sub-populations utilise to modulate stiffness during sport specific task demands. *(Focus of Chapter 7)*

4- To assess the longitudinal differences across a season of training (pre, post and off season) in leg stiffness in different female athletic sub-populations from varied training backgrounds during repeated hopping and sports-specific tasks. Additionally, to prospectively evaluate the associated lower-body injury risk in athletes. *(Focus of Chapter 8)*

3.8 Importance of Chapter 5

The systematic review established a need to evaluate the influence of varied athletic training backgrounds on leg stiffness, joint stiffness and the contributory mechanisms to stiffness control. Evaluation of diverse athletic training backgrounds during discrete jumping tasks may enhance the existing knowledge of the influence of chronic athletic training on lower-extremity stiffness and associate links to performance and injury.

Following the extended methodology Chapter 5 evaluated Aim 1 of the thesis:

Aim 1 – To investigate the differences in leg and joint stiffness between athletes from varied training backgrounds during discrete jumping tasks traditionally utilised to assess stiffness. Further, to evaluate the kinematic and kinetic mechanisms athletic populations utilise to modulate stiffness.

Chapter 4. Extended Methodology

The specific experimental chapters contained in this thesis are designed as stand-alone publications and as such contain a methodology section specific to each papers testing procedures. This chapter represents an overview of the generic methodological elements related to the overall research project, including research design, participant recruitment and general test procedures (data collection and analysis).

4.1 Research Design

To meet the general aims of this thesis to evaluate the influence of varying training types on stiffness, performance and injury, a longitudinal observational design was implemented. To further explore the general aims, this research project consisted of four specific stand-alone studies with varying study designs relevant to the aims and hypothesis of each individual paper (Table 4.1).

Table 4.1- *Study Design Breakdown for Stand-Alone Papers.*

Study	Title	Experimental Design
1	Lower body stiffness modulation strategies in well trained female athletes	Cross sectional
2	Variations in lower body stiffness during sports-specific tasks in well trained female athletes	Cross sectional
3	Variations in lower body stiffness modulation strategies during sports-specific tasks in well trained female athletes	Cross sectional
4	Longitudinal lower body stiffness variations and associated injury risk during sports-specific tasks in well trained female athletes	Longitudinal

In order to increase the practical application of findings for coaches, athletes and practitioners, this research focused on unilateral stiffness (participant's dominant leg) of the leg spring during the eccentric phase of movement. Unilateral stiffness was chosen as few locomotive movements in the sporting realm are preformed bilaterally (Ackland, Elliot, & Bloomfield, 2009).

4.2 Ethics Approval

Testing procedures were approved by the Australian Catholic University Human Research Ethics Committee (Appendix C). Following ethical clearance, potential participants were provided with information letters informing them of the objectives, requirements and procedures prior to providing written informed consent to the research team (Appendix D). Parental consent was obtained for subjects who were under the age of 18 (Appendix E).

Data collection methods and procedures associated with the research were considered low risk to the participants, whereby the only foreseeable risk was the possibility of muscle strain during jumps which was not above typical training levels and the inconvenience of giving up time in order to participate in the project. To minimise the risk of discomfort, participants were provided with sufficient rest periods between tasks. The research team made it clear to participants that they reserved the right to cease participation without explanation at any time throughout the duration of the project. Under no circumstances through the duration of the research were participants coerced into partaking in the research.

All data was de-identified via coding where possible during data collection in order to maintain anonymity. Only group data was published in order to ensure individual characteristics were unable to be identified through results.

4.3 Participants

4.3.1 Estimated Sample Size

Based on the research of Hobara, Kimura, et al. (2010) which investigated stiffness differences between endurance athletes and non-athletes, an a-priori power analysis for F statistics (ANOVA) revealed a total sample size of N=36 (sub-population n=12; p=0.05, ES = 0.7) was required for sufficient statistical power ($1 - \beta = 0.8$) (Kraemer & Theimann, 1987). This study was selected due to the inclusion of dynamics tasks and recruited participants which were deemed the closest population comparison to the investigated groups of this study.

4.3.2 Participant Recruitment

Participants were recruited from three distinct habitual training backgrounds to represent three varying types of athletic training and practice (Gambetta, 2007; Garrett & Kirkendall, 2000; Siedentop, 2007). These training backgrounds included endurance, high intensity intermittent and non-active controls. Participants were grouped based on their training regime against the criteria outlined below in Table 4.2.

Table 4.2- *Training Type Criteria.*

Training Type	Description	Population Recruited
Endurance	Continuous sustained exercise for a minimum of 20 minutes. Aerobic exercise that aims to increase stamina and endurance.	Track and Field- Middle distance; Endurance runners
High Intensity Intermittent	Form of interval training consisting of short bouts of all out exercise separated by rest periods between 20 secs to 5 minutes. Evident in team sports.	Netballers
Control	Non-active group with no previous specific training background. May engage in sporadic bouts of exercise or lead a sedentary lifestyle.	General Population

Forty-seven female participants (20 nationally identified netballers, 13 high level endurance athletes and 14 age and gender matched controls) volunteered to participate in this research (Table 4.3). Netball and endurance athletes were recruited through distributed flyers at the New South Wales Institute of Sport, affiliated coaches and New South Wales based district athletic clubs. Athletic populations were required to compete at a national level (see section 4.3.3). Control participants were targeted through advertised flyer's at the Australian Catholic University. Despite potential variations between training backgrounds and training history due to the set national level standard, it was assumed that the athletes were of a similar athletic standard given their competition level.

Table 4.3- *Participant Descriptive Information. Values are mean (SD).*

Group	N	Age (Years)	Mass (kg)	Height (cm)	Average Training Hours ($h \cdot wk^{-1}$)	Training Years
Netball	20	17.4 (1.5)	69.2 (8.4)	178.1 (5.6)	7.9 (4.8)	6.4 (3.6)
Endurance	13	19.7 (4.0)	53.4 (2.9)	165.9 (4.8)	10.0 (3.4)	7.5 (2.5)
Control	14	22.1 (2.3)	59.6 (9.9)	162.9 (5.5)	2.1 (1.2)	-

Due to the longitudinal nature of the project participant dropout did occur as a result of participant availability, injury and illness. Figure 4.1 outlines the participant dropout through the duration of the research.

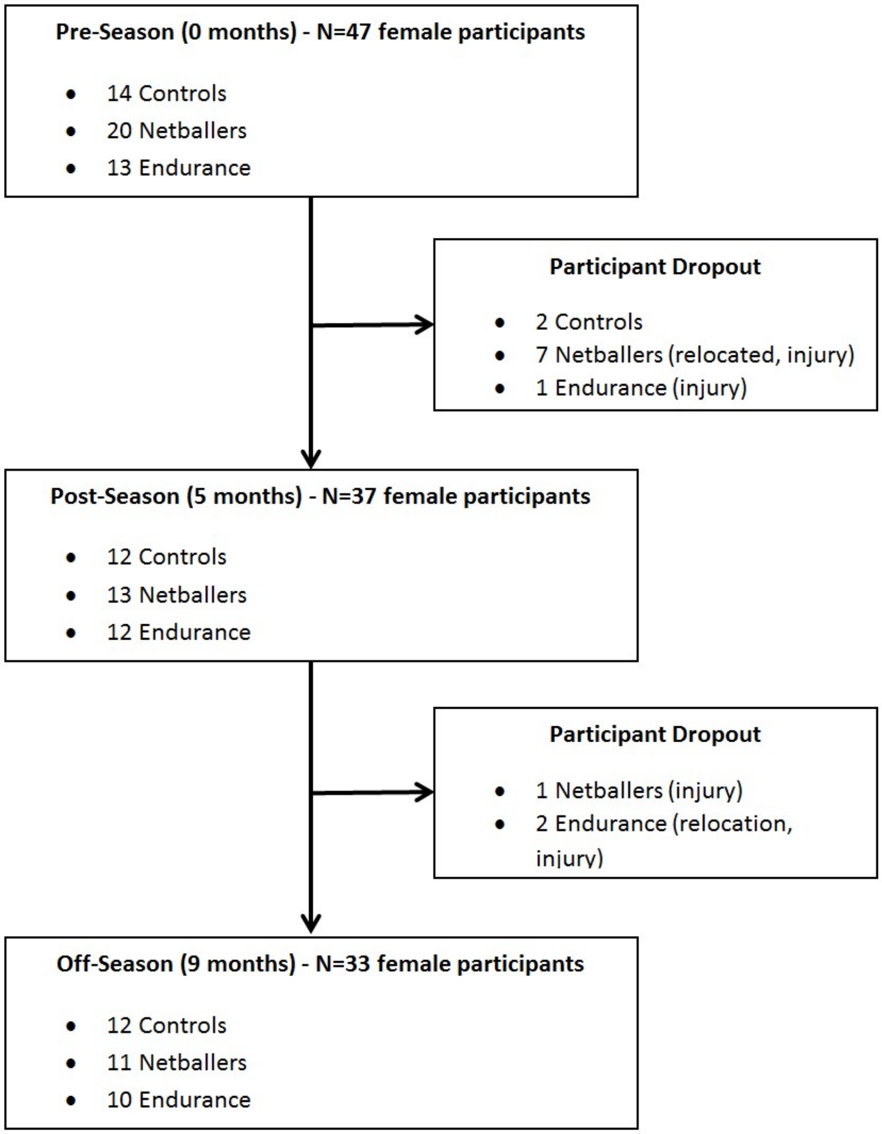

Figure 4.1- Participant dropout through the duration of the study.

4.3.3 Inclusion/Exclusion Criteria

Research has established that variations in leg stiffness between male and female participants exist (Padua et al., 2006). In order to ensure gender differences did not confound the results of the research, participants were limited to female athletes aged between 16 to 30 years of age. Females were targeted due to the higher prevalence and risk of injury when compared to their male counterparts. Furthermore, female athletes are under reported within the lower-extremity stiffness and athletic training literature.

For athletes to be included in the research, participants were required to meet the follow inclusion criterion:

- To ensure growth and maturation did not influence stiffness measures, all participants were to meet full physical maturation guidelines. End of physical maturation was defined as 2 years post menarche indicative of the final stage of puberty i.e. Stage 5, assessed via self-reported questionnaire (Appendix F) (Marshall & Tanner, 1969).
- Participants were to be healthy and free from lower limb injuries. Injury-free was defined as not missing or modifying two consecutive training/competition sessions in the two week period prior to testing, assessed via self-reported questionnaire (Appendix F) (Kirialanis, Malliou, Beneka, & Giannakopoulos, 2003).
- Age and gender matched control participants were not to exceed four hours of weekly physical activity and to have no competitive or sport specific training history, assessed via self-reported questionnaire (Appendix F).
- Netball and endurance athletes were to have met the qualification standards/selection guidelines outlined for their relevant national championships. National entry standards for Endurance athletes were determined by Athletic Australia and Netball athletes were required to be selected into a national level squad. Athletes were required to be participating in a minimum of four sports-specific sessions of more than 30 minutes in duration per week.

Athletes were excluded if they regularly engaged in aquatic sports such as swimming and waterpolo. Although the training may be maximal and/or endurance in nature, as the activities are non-weight bearing, the musculoskeletal and subsequent stiffness adaptations may vary when compared to weight bearing training.

4.4 Testing Procedures

Participants attended three testing sessions across a regular training season with each lasting for 90 minutes. Data was collected at three time points during the athlete's regular training cycle; pre (0 months), post (5 months) and off season (9 months). These specific phases were targeted due to the varying training loads associated with periodisation and to minimise interference with an athlete's training and competition schedule. As control participants did not have specific training phases, duration between test sessions was matched to that of the recruited athletic populations.

Prior to data collection descriptive information regarding age, athletic background, exercise history and women's menstrual cycle (age of first menarche) was gathered to ensure participants meet the outlined inclusion criteria (Appendix F). To ensure data was representative of the daily training environment participants were instructed to perform tasks in their regular training shoes and discouraged from engaging in strenuous exercise 24 hours prior to testing. Prior to data collection participants performed a self-directed, whole body dynamic warm up and refrained from undertaking passive stretching due to the negative impact on neuromechanical variables (Meylan, Nosaka, Green, & Cronin, 2010). The warm up consisted of a combination of approximately 5-10 minutes of jogging or cycling on an exercise bike followed by 10 minutes of simple dynamic, lower body mobility drills (e.g. high knees, landing and agility drills). Participants were advised to wear minimal clothing (i.e. tight bike shorts and crop top) to avoid losing view of reflective markers and reduce artifactual movement during the experimental movement tasks.

Participants were asked to complete six unilateral lower body stiffness screening tasks. These tasks ranged from basic discrete jumping tasks traditional utilised to assess stiffness to dynamic sports-specific tasks. Tasks classed as "traditional" stiffness methods frequently used to evaluate leg and joint stiffness included countermovement jump (CMJ) (see section 4.4.1), drop jump (DJ) (see section 4.4.2) and horizontal jump (HJ) (see section 4.4.3) (Ambegaonkar et al., 2011; Hunter & Marshall, 2002; Kubo et al., 2007). Tasks deemed dynamic and reflective of the daily training and competition environment included sprint (see section 4.4.4), anticipated sidestep cutting tasks (see section 4.4.5) and repetitive hopping (see section 4.4.6). Five successful trials were captured of each task on the participant's dominant leg, with the exception of the repeat jumps task which required only one successful trial due to the number of multiple contacts collected during the trial. Leg dominance was defined using a modified protocol based on the methods of Padua et al. (2006). This required participants to perform a single leg landing drop jump from a 0.30 m box; whereby participants self-selected the preferred landing leg prior to a reactive rebound jump. Dominance was defined as the successful landing leg in at least two of three trials.

Following a demonstration, participants performed familiarisation trials of each task until participants were comfortable with the task and displayed a continuous coordinated movement pattern. To maintain the validity of jump data, target heights were set using a Vertec (Access Health, Victoria, Australia) to ensure participants aimed to achieve maximal vertical height. Target heights were determined during familiarisation and were set at a vertical eye height greater than that achieved during practice trials. During jump tasks participants were instructed to position their hands on their hips in order to minimise the contribution of arm swing to jump height and distance (Harman, Rosenstein, Frykman, & Rosenstein, 1990; Luhtanen & Komi, 1979). Intra and inter session task order was randomised to eliminate any order effects, with the exception of the repeat jumps task which was performed last to ensure fatigue did not bias results.

4.4.1 Countermovement Jump (CMJ)

Participant's assumed a stable single-leg stance position on their dominant limb on the force plate with a raised non-dominant leg. Once stable participants were advised to lower their centre of mass in a vertical downward motion at a pace of their choosing and then perform one maximal effort jump aiming to achieve maximal vertical distance from the ground indicated by a target set at a vertical eye height determined through familiarisation (Figure 4.2). Participants were discouraged from swinging the contralateral limb and instructed to keep their hands on their hips in order to minimise the contribution of arm swing to jump height. Data was collected from the point of stability and leg stiffness and joint stiffness measures were evaluated during the eccentric phase of jump preparation. Trials were visually inspected and eliminated if they did not meet jump criteria i.e. did not meet jump height set during familiarisation, landed off the force plate, hands left the hips, used the contralateral limb to generate jump height or did not resume a stable position. As participants were required to perform five maximal effort trials, participants were instructed to rest until they felt fully recovered between trials.

Figure 4.2- Movement breakdown of countermovement jump task.

4.4.2 Drop Jump (DJ)

Participants were advised to step off a 0.40 m box, land on their dominant leg and perform one unilateral vertical jump aiming to achieve maximal vertical distance from the ground indicated by a target set at a vertical eye height determined through familiarisation (Figure 4.3). Participants were instructed to keep their hands on their hips in order to minimise the contribution of arm swing to jump height and discouraged from swinging the contralateral limb to generate jump height. To ensure the jump was reactive in nature, participants were instructed to minimise ground contact time. The 0.40 m drop height was selected as it was the most commonly reported height in previous stiffness literature assessing during this task (Ambegaonkar et al., 2011; Arampatzis et al., 1999; Arampatzis et al., 2004). Trials were visually inspected and eliminated if they did not meet jump criteria i.e. did not meet jump height set during familiarisation, contact was not reactive in nature, landed off the force plate, hands left the hips or used the contralateral limb to generate jump height. As participants were required to perform five maximal effort trials, participants were instructed to rest until they felt fully recovered between trials. Drop jump leg and joint stiffness measures were isolated to the eccentric phase of movement i.e. from the instance of contact to point where the centre of mass reached the lowest point of displacement during contact.

Figure 4.3- Movement breakdown of drop jump task.

4.4.3 Horizontal Jump (HJ)

In order to quantify stiffness during a discrete basic jumping task with a 'dynamic' horizontal component, a modified reactive horizontal jump protocol was utilised (Stalbom, Holm, Cronin, & Keogh, 2007). Participants were instructed to resume a static two feet standing position directly behind the frame of the force plate (4.5cm). Participants then performed a countermovement jump to land on the force plate with their dominant leg followed by a horizontal jump aiming to achieve maximal horizontal distance (Figure 4.4). Target distance determined through familiarisation trials was set to ensure participants aimed to achieve maximal horizontal distance. Participants were instructed to keep their hands on their hips in order to minimise the contributions of arm swing to jump distance, they were also discouraged from swinging the contralateral limb and advised to minimise ground contact to ensure the jump was reactive in nature. Trials were visually inspected and eliminated if they did not meet jump criteria i.e. did not meet jump distance set during familiarisation, contact was not reactive in nature, landed off the force plate, hands left the hips or used the contralateral limb to generate jump distance. As participants were required to perform five maximal effort trials, participants were instructed to rest until they felt fully recovered between trials. Horizontal jump leg and joint stiffness measures were isolated to the eccentric phase of movement i.e. from the instance of contact to the point where the centre of mass reached the lowest point of displacement during contact.

Figure 4.4- Movement breakdown of horizontal jump task.

4.4.4 Sprinting

Sprinting is reflective of a standard activity relevant in most training and competition sporting environments. Participants were advised to complete a 40 metre sprint at a velocity representative of training and competition pace (Figure 4.5). Participants were instructed started the sprint 30 metres from the force plate which allowed participants to generate necessary speed and were advised to continue running 10 metres past the plates indicated by tape marks. Start points were adjusted by the researcher to allow participants to strike the force plate without deviating from their normal line to achieve this. Due to the high level nature of the netball and endurance athletes, these participants were adequately able to maintain game-play and race-pace velocity, respectively. As control participant did not have a regular training and competition pace, they were advised to complete trials at a pace representative of a run. To ensure trials replicated the daily training environment participants were discouraged from decelerating or overextending to strike the plate, with trials displaying these qualities deemed unsuccessful. Trials were also eliminated if the velocity was not consistent with the average representative running velocity of the individual. Data was captured one stride prior to and following contact with the force plate. Leg stiffness and joint stiffness measures were isolated to the eccentric phase of movement i.e. the instance of contact to the point where the centre of mass reached the lowest point of displacement during contact. Trials were repeated until five successful contacts on the force plate were achieved. As participants were required to perform five successful trials, participants were instructed to rest until they felt fully recovered between trials.

Figure 4.5- Movement breakdown of sprinting task.

4.4.5 Anticipated Sidestep Cutting Task

The anticipated sidestep cutting task was targeted due to the relevance to high intensity intermittent sporting populations where rotation movements about a joint occur to achieved direction change is needed. Participants were instructed to start the task 15 metres from the force plate and accelerate out of the change of direction for 5 meters as indicated by tape (Figure 4.6). Participants were also advised to approach at a velocity reflective of training and competition. As control participants did not have a regular training and competition pace, they were advised to complete trials at a pace representative of a run. The demands of the task required participants to land on their dominant leg and push diagonally sideways with the non-dominant leg landing between 30 to 40 degrees relative to the direction of movement at the contact point of the dominant leg. This angle was marked on the floor and was selected as it represented directional change in typical high intensity intermittent game situations (McLean, Lipfert, & Van Den Bogert, 2004). Trials were eliminated if participants adjusted their stride in order to strike the force plate, if the non-dominant leg did not land between 30 to 40 degrees and if the velocity was not consistent with the average representative running velocity. Data was captured one stride prior to and following contact with the force plate. Leg stiffness and joint stiffness measures were isolated to the eccentric phase of movement i.e. the instance of contact to the point where the centre of mass reached the lowest point of displacement during contact. Trials were repeated until five successful contacts on the force plate were achieved. As participants were required to perform five successful trials, participants were instructed to rest until they felt fully recovered between trials.

Figure 4.6- Movement breakdown of anticipated sidestep cutting task.

4.4.6 Repetitive Hopping

The repetitive hopping task provided a representation of an intermediate dynamic task between the basic jump tasks and sport specific movements. Participant's assumed a stable single-leg stance position on their dominant limb on the force plate with a raised non-dominant leg. Once in a stable position participants were advised to perform 27 continuous reactive hops at a self-selected sub-maximal intensity, the first five and last two trials were excluded from analysis (Figure 4.7) (Moresi, Bradshaw, Greene & Naughton, 2014). Submaximal was defined as 70% of the maximal jump height achieved during the countermovement jump task indicated by a set target height ensuring the repeatability of jump data. A self-selected pace was utilised in order to reflect typical training demands of athletes. Participants were discouraged from swinging the contralateral limb. Participants were also instructed to keep their hands on their hips in order to minimise the contribution of arm swing to jump height and to minimise horizontal displacement movement of the force plate during the task. Visual inspection of trials was undertaken to ensure trials meet a jump criteria of continuous vertical jump movement, achieved determined target height, minimised swing of contralateral limb. Trials were repeated if excessive horizontal movement occurred or jump criteria were violated. Leg stiffness measures were isolated to the eccentric phase of movement this was defined as the instance of contact to the lowest point of displacement in the centre of mass during ground contact. Literature has established a relationship between jump frequency and leg stiffness (Hobara et al., 2013; Hobara et al., 2011), and jump frequency was statistically controlled for in the analysis accordingly.

Figure 4.7- Movement breakdown of repetitive hopping.

4.4.7 Data Collection

Kinematic data was captured using a ten camera motion analysis system sampling at 500 Hz (Vicon MX, Oxford Metrics Ltd., Oxford, United Kingdom) (Figure 4.8). The standard 35 marker Vicon Plug-in-gait full body model (Vicon; Oxford Metrics Ltd., Oxford, United Kingdom) was utilised to determine centre of mass displacement (Table 4.4 and Figure 4.9). This model has shown to be reliable and valid for the assessment of sagittal plane kinematics (Doma, Deakin, & Sealey, 2012; McGinley, Baker, Wolfe, & Morris, 2009). Kinetic data was obtained using ground mounted force plates sampling at 1000 Hz, covered with a Mondo track surface (Advanced Mechanical Technology Inc., Watertown, U.S.A. and Kistler, 9281CA, Switzerland).

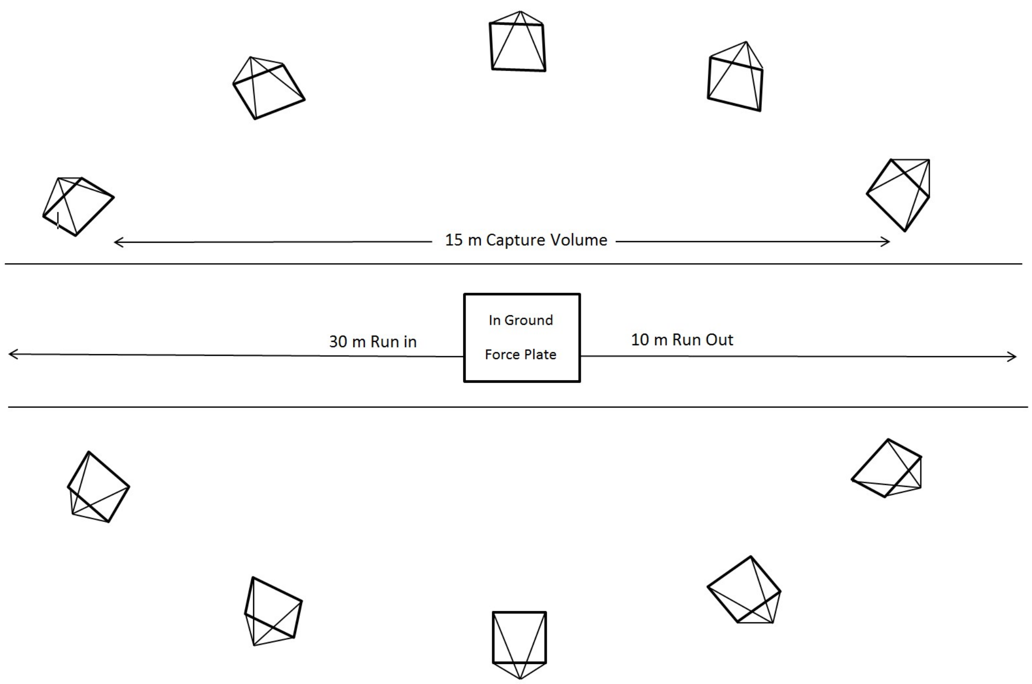

Figure 4.8- Laboratory configuration.

Table 4.4- Definition of Anatomical Locations for Marker Placement (Vicon; Oxford Metrics Ltd., Oxford, United Kingdom)

	Marker	Location of Marker
1	Left Front Head	Left temple
2	Right Front Head	Right temple
3	Left Back Head	Left back of temple (defines the transverse plane of the head, together with the frontal markers)
4	Right Back Head	Right back of head (defines the transverse place of the head, together with the frontal markers)
5	7th Cervical Vertebra	Spinous process of the 7th cervical vertebra
6	10th Thoracic Vertebra	Spinous process of the 10th thoracic vertebra
7	Clavicle	Jugular notch where the clavicles meet the sternum
8	Sternum	Xiphoid process of the sternum
9	Right Back	Over the right scapula
10	Left Shoulder	Acromio-clavicular joint
11	Left Elbow	Lateral Epicondyle
12	Left Wrist Marker A	Thumb side of the left wrist
13	Left Wrist Marker B	Little finger side of the left wrist
14	Left Finger	Proximal to the middle knuckle on the left hand
15	Right Shoulder	Acromio-clavicular joint
16	Right Elbow	Lateral epicondyle
17	Right Wrist Marker A	Thumb side of the right wrist

	Marker	Location of Marker
18	Right Wrist Marker B	Little finger side of the right wrist
19	Right Finger	Proximal to the middle knuckle on the right hand
20	Left Anterior Superior Iliac Spine	Left anterior superior iliac spine
21	Right Anterior Superior Iliac Spine	Right anterior superior iliac spine
22	Left Posterior Superior Iliac Spine	Left posterior iliac spine immediately below the sacro-iliac joint, at the point where the spine joins the pelvis
23	Right Posterior Superior Iliac Spine	Right posterior iliac spine immediately below the sacro-iliac joint, at the point where the spine joins the pelvis
24	Left Thigh	Lower later third surface of the left thigh on the line from the greater trochanter and knee joint centre
25	Left Knee	Flexion-extension axis of the left knee
26	Left Tibia	Lower third surface of left shank on the line from knee joint centre and lateral malleolus
27	Left Ankle	Lateral malleolus along an imaginary line that passes through the transmalleolar axis
28	Left Heel	Calcaneous at the same height above the plantar surface of the foot as the toe marker
29	Left Toe	Second metatarsal head, on the mid-foot side of the equinus break between fore-foot and mid-foot
30	Right Thigh	Upper third surface of left shank on the line from knee joint centre and lateral malleolus
31	Right Knee	Flexion-extension axis of the left knee

	Marker	Location of Marker
32	Right Tibia	Upper third surface of left shank on the line from knee joint centre and lateral malleolus
33	Right Ankle	Lateral malleolus along an imaginary line that passes through the transmalleolar axis
34	Right Heel	Calcaneous at the same height above the plantar surface of the foot as the toe marker
35	Right Toe	Second metatarsal head, on the mid-foot side of the equinus break between fore-foot and mid-foot

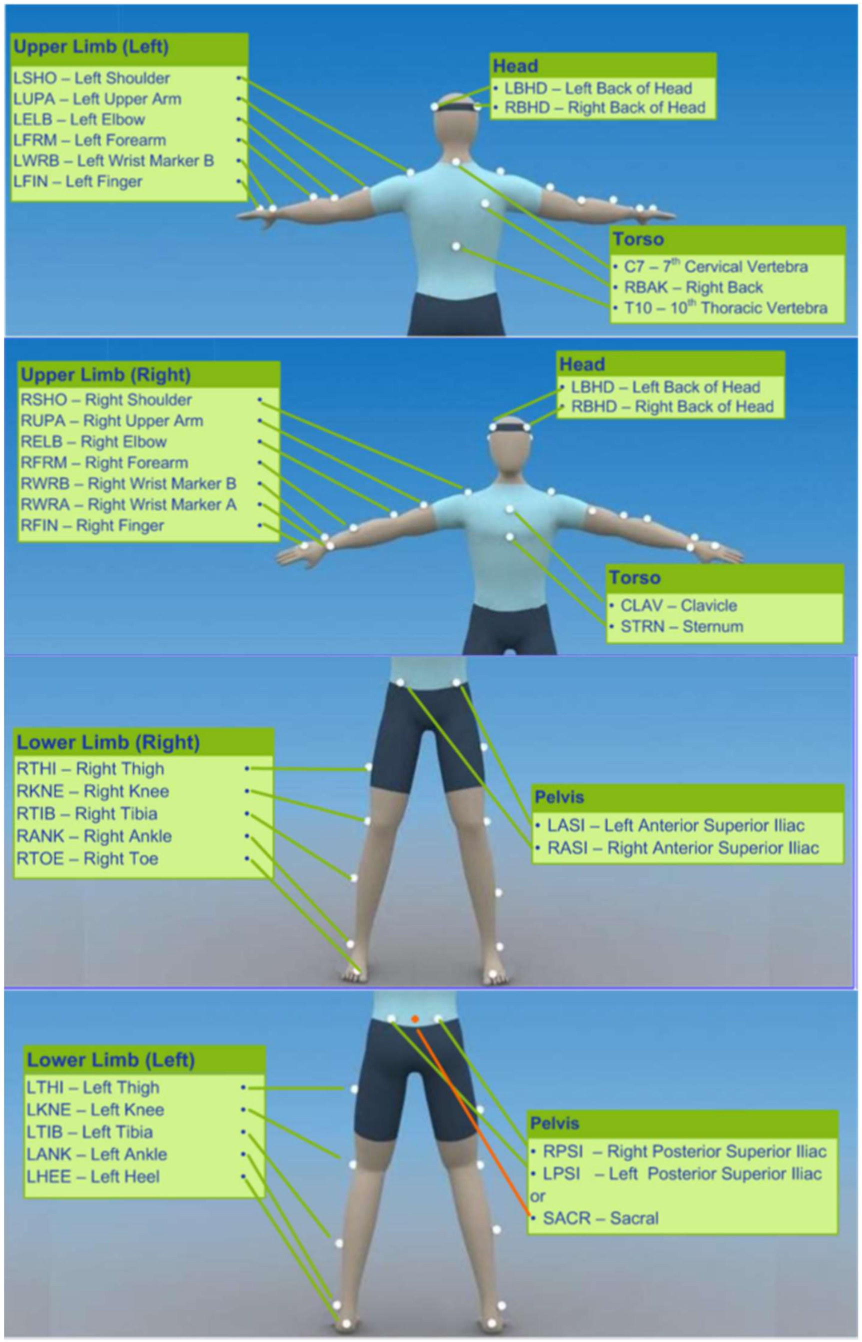

Figure 4.9- Vicon Plug-in-gait full body model marker locations (Vicon; Oxford Metrics Ltd., Oxford, United Kingdom)

4.4.8 Data Analysis

Following analysis of the frequency content and residuals of the power spectra in kinematic data (Winter, 2005) a cut off frequency of 16 Hz for jump data; inclusive of countermovement jump, drop jump, horizontal jump and repeat jump; and 23 Hz for sprint and anticipated change of direction tasks was utilised in a dual, low pass, fourth order Butterworth filter. Force plate data was not filtered to ensure leg and joint stiffness data was not confounded by filtering techniques subsequently effecting joint kinetic measures (Bezodis, Salo, & Trewartha, 2013; Diggin, Anderson, & Harrison, 2016). Filtering was undertaken through Vicon with kinematic and kinetic data outputted to allow for leg and joint stiffness calculations to be derived through customised Excel spreadsheets (Microsoft Excel 2010; Washington United States). Leg and joint stiffness measures were isolated to the eccentric phase of movement during each of the five tasks and hence during the period of elastic energy storage in muscle tendon complexes.

4.4.9 General Test Measures

Table 4.5 contains a detailed breakdown of the specific tasks and assessed variables evaluated in each of the relevant chapters in order to evaluate the influence of athletic training on functional lower-extremity stiffness.

Table 4.5- *Overview of Tasks and Variables Assessed in Each Study.*

Study	Tasks	Variables Assessed
1- Lower body stiffness modulation strategies in well trained female athletes	Countermovement Jump Drop Jump Horizontal Jump	Leg Stiffness
2- Variations in lower body stiffness during sports-specific tasks in well trained female athletes	Sprint Anticipated Change of direction Repetitive Hopping	Leg Stiffness Performance Variables (Centre of mass displacement, contact time, peak vertical force, horizontal velocity, jump height, jump frequency)
3- Variations in lower body stiffness modulation strategies during sports-specific tasks in well trained female athletes	Sprint Anticipated Change of direction Repetitive Hopping	Leg Stiffness Joint Stiffness Contributing Kinematic Mechanisms
4- Longitudinal lower body stiffness variations and associated injury risk during sports-specific tasks in well trained female athletes	Sprint Anticipated Change of direction Repetitive Hopping	Leg Stiffness Training Hours Injury Incidence

4.4.9.1 Leg Stiffness

Leg stiffness scores were determined using methodology presented by McMahon and Cheng (1990) (equation 12), whereby stiffness equated to the peak vertical ground reaction force (PVGRF) divided by the change in leg length. The change in leg length incorporates the initial leg length of the participant, vertical displacement of the centre of mass, horizontal velocity at impact and contact time (equation 13 and 14). Although vertical stiffness calculations are traditionally utilised to determine stiffness during vertical jumps such as countermovement jump, drop jump and repeat hopping, previous literature has established that stiffness derived using the vertical stiffness formula equates to leg stiffness scores during vertical jump tasks (Butler et al., 2003). Due to the inclusions of the horizontal jump, sprint and anticipated change of direction cutting tasks, leg stiffness calculations were required and implemented to assess each task to ensure consistency. The McMahon and Cheng (1990) methodology was utilised at it is the most common formula within stiffness literature and as such allows for comparisons to previous research.

Equation 12- $K_{Leg} = \frac{F_{max}}{\Delta L}$

Equation 13- $\Delta L = \Delta y + L_0(1 - cos\theta)$

Equation 14- $\theta = \sin(\frac{vt_C}{2L_0})$

Where F_{max} = peak vertical ground reaction force; ΔL = change in vertical leg length; Δy = vertical displacement of the centre of mass; L_0 = initial leg length; θ = half angle of the arc swept by the leg; v = horizontal velocity at touchdown; t_c = contact time.

To provide a typical representation of each individual's leg spring and contributing mechanistic variables for each task with the exception of the repetitive hopping task, the highest and lowest stiffness scores were eliminated. The mean of the remaining middle three scores were implemented in subsequent analysis (Moresi et al., 2014). The associated joint stiffness and contributing mechanisms of excluded trials were also removed.

Research has established a relationship between jump frequency, running velocity and stiffness, whereby as velocity and jump frequency increases stiffness also increases (Arampatzis et al., 1999). As participants were performing tasks at a self-selected pace, variations in jump frequency and running velocity between individuals and populations were present. To ensure leg stiffness measures were comparable across all participants, scores were normalised to body weight and standardised to the average horizontal touchdown velocity/jump frequency of all participants using population specific residual calculations derived from linear regression analysis (Table 4.6). Mass-normalised stiffness values were plotted against velocity to establish a regression equation for each sub-population. The residual distance for each athlete from the regression line was used to calculate a normalised stiffness value for each participant for the mean velocity or jump frequency score. Longitudinal evaluation utilised population specific average pre-season horizontal touchdown velocity/jump frequency in training phase specific residual calculations derived from linear regression analysis (Table 4.6). Individual population residual calculations were utilised due to variations in the linear regression slopes between groups.

Table 4.6- *Population Specific Running Velocity and Jump Frequency Utilised in Linear Regression to Normalise Stiffness Values.*

Task	Normalised Velocity and Jump Frequency
Cross Sectional Design (Study 2 and 3)	
Sprint	5.72 m/s
Anticipated Sidestep Cutting Task	4.62 m/s
Repetitive Hopping	1.86 Hz
Longitudinal Design (Study 4) – Pre Season	
Netball- Sprint	5.90 m/s
Netball- Anticipated Sidestep Cutting Task	4.58 m/s
Netball- Repetitive Hopping	1.79 Hz
Endurance- Sprint	6.06 m/s
Endurance- Anticipated Sidestep Cutting Task	4.95 m/s
Endurance- Repetitive Hopping	1.88 Hz
Control- Sprint	4.99 m/s
Control- Anticipated Sidestep Cutting Task	4.33 m/s
Control- Repetitive Hopping	1.97 Hz

4.4.9.2 Joint Stiffness

Joint stiffness of the hip, knee and ankle were determined using the methodology outlined in Farley et al., (1998), where stiffness of the joint equated to the ratio of the change in joint moment to the angular displacement of the joint during the eccentric phase of movement (initial contact to mid-stance) (equation 15). This particular method of determining stiffness of the joint is the most common method reported through the literature.

Equation 15- $K_{Joint} = \frac{\Delta J_m}{J_d}$

Where ΔJ_m = Change in joint moment during the eccentric phase of movement; J_d = Joint angular displacement.

4.4.9.3 Reliability of Leg and Joint Stiffness Measures

Previous research has suggested joint stiffness in running may be unreliable (Joseph, Bradshaw, Kemp, & Clark, 2013). Thus to ensure stiffness changes observed across a season were representative of training associated variations, reliability of leg and joint stiffness derived from the sprint and anticipated change of direction cutting task were assessed. Leg stiffness reliability is well established for countermovement jump, horizontal jump and repetitive hopping (Table 4.7). Eleven female control participants were recruited, as it was hypothesised that this population would display a higher degree of movement variability compared to athletic populations (Table 4.8). To evaluate inter-session reliability participants were asked to attend two testing sessions separated by a week and instructed to perform five trials of the sprint and anticipated change of direction cutting task. Methodology was in line with the procedures outlined previously in this chapter regarding test procedure, data acquisition and analysis.

Table 4.7- *Reliability Statistics For Countermovement Jump, Horizontal Jump and Repetitive Hopping Tasks.*

Task	Study	ICC	CV%	Reliable
Countermovement Jump	Moir, Garcia & Dwyer, 2009	0.78-0.95	5.1-9.3	Yes
Horizontal Jump	Stalbom et al., 2007	0.74-0.96	2.26-8.28	Yes
Repetitive Hopping	Pruyn et al., 2013	0.80	4.15	Yes

Table 4.8- *Descriptive Statistics of Participants Undertaking the Reliability Analysis. Values are mean (SD).*

N	Age (Years)	Mass (kg)	Height (cm)
11	25.7 (2.5)	67.6 (15.5)	165.5 (7.0)

Mean, standard deviations, intra-class correlation coefficient (ICC) and coefficient of variations (CV) were determined using Hopkins (2000) two-way analysis spreadsheets. Leg and joint stiffness measures were log transformed to estimate errors. Measures were deemed reliable if data displayed an ICC of greater than 0.90 and a CV% of less than 10% (Atkinson & Nevill, 1998). Table 4.9 provides a breakdown of mean, standard deviations, ICC and CV% for leg and joint stiffness measures during sprint and anticipated change of direction cutting tasks.

Table 4.9- *Leg Stiffness Measures and Reliability Statistics for Sports-Specific Tests.*

Measure	Mean (SD) Week 1	Mean (SD) Week 2	ICC	CV%	Reliable
Sprint					
Leg Stiffness ($N^{-1}\cdot m^{-1}\cdot kg^{-1}$)	107.72 (25.02)	109.81 (30.44)	0.98	5.6	Yes
Hip Stiffness ($N\cdot m^{-1}\cdot deg^{-1}\cdot kg^{-1}$)	0.314 (0.288)	0.273 (0.169)	0.32	201.7	No
Knee Stiffness ($N\cdot m^{-1}\cdot deg^{-1}\cdot kg^{-1}$)	0.118 (0.029)	0.133 (0.038)	0.45	23.2	No
Ankle Stiffness ($N\cdot m^{-1}\cdot deg^{-1}\cdot kg^{-1}$)	0.128 (0.035)	0.112 (0.031)	0.85	11.8	No
Anticipated Change of Direction Cutting					
Leg Stiffness ($N^{-1}\cdot m^{-1}\cdot kg^{-1}$)	101.91 (33.63)	100.79 (28.57)	0.95	8.2	Yes
Hip Stiffness ($N\cdot m^{-1}\cdot deg^{-1}\cdot kg^{-1}$)	0.122 (0.172)	0.242 (0.175)	0.26	267.2	No
Knee Stiffness ($N\cdot m^{-1}\cdot deg^{-1}\cdot kg^{-1}$)	0.115 (0.0340	0.115 (0.026)	0.38	26.2	No
Ankle Stiffness ($N\cdot m^{-1}\cdot deg^{-1}\cdot kg^{-1}$)	0.104 (0.028)	0.098 (0.035)	0.72	20.0	No

Results established that leg stiffness measures appeared to display good intra-session reliability, while joint stiffness measures of the hip, knee and ankle appeared unreliable. Although it may appear that joint stiffness measures were unreliable, recent research has suggested reliability results indicate inherent individual variability in movement as opposed to measurement error (Diggin et al., 2016). ICC and CV% results appeared to improve through the eccentric kinematic chain, suggesting joints higher up the chain may be more variable (e.g. the hip joint appeared more variable then the knee while the ankle joint was less variable than the knee joint). It can be speculated based on previous research that control participants displayed an individualised joint control strategy during sprint and change of direction tasks, and as a result may display higher variability and unreliability (Millett, Moresi, Watsford, Taylor, & Greene, 2015). It could be suggested that athletic populations may display more agreeable reliability. As joint stiffness measures appeared unreliable or may be an individualised approach, these measures were excluded from longitudinal study evaluation. It was deemed relevant to evaluate joint stiffness measures in the cross sectional studies as it was considered pertinent given suggestions that joint stiffness reflects a control strategy of leg stiffness measures.

4.4.9.4 Contributing Mechanisms

Understanding the kinematic and kinetic mechanisms populations utilise to meet task demands provides insight into the ways individuals from varying training backgrounds modulate stiffness. The contributing kinematic mechanisms assessed included joint displacement, joint moment and touchdown angles of the hip, knee and ankle. Performance measures reflects global outcome measures related to performance of tasks these include peak vertical ground reaction force, centre of mass displacement, contact time, touchdown velocity and jump height. Jump height was derived using the impulse method (Linthorne, 2001). Assessment of the underlying contributing kinematic, kinetic and performance measures is key to gaining an increased understanding of the mechanisms and adjustments at the joint level which influence leg stiffness and joint stiffness modulation to meet performance demands.

4.4.9.5 Anthropometric Measures

Anthropometric measures were obtained prior to each testing session following the International Society for the Advancement of Kinanthropometry (ISAK) protocol. Height and weight were obtained using a stadiometer, accurate to ± 0.01 m (SECA height rob model, Hamburg, Germany) and digital scales accurate ± 0.05 kg. Standard limb lengths and joint widths were determined using an anthropometer accurate to 0.001 m; and utilised in the Vicon Plug-in-gait model (Table 4.10). All measures were assessed using one trained anthropometrist.

Table 4.10- *Limb Length and Joint width Descriptives for Vicon Plug-in-gait Model (Vicon; Oxford Metrics Ltd., Oxford, United Kingdom).*

Measure	Description
Leg Length	Full leg length measured between the anterior superior iliac spine marker and the medial malleolus, via the knee joint. Measure with athlete stand
Knee Width	Medio-lateral width of the knee across the line of the knee axis
Ankle Width	Medio-lateral distance across the malleoli
Elbow Width	Width of the elbow along flexion axis between the medial and lateral epicondyles of the humerus
Wrist Width	Anterior/posterior thickness of the wrist as position where wrist marker is attached
Hand Thickness	Anterior/posterior thickness between the dorsum and palmar surfaces of the hand
Shoulder Offset	Vertical offset from the base of the acromion marker to shoulder joint centre

4.4.9.6 Training Load and Training Hours

To assess the longitudinal impact of training on lower limb stiffness, external training load was monitored through weekly online training diaries for the duration of the project (Appendix G). This required participants to complete brief details pertaining information regarding training sessions including session type, duration and perceived rate of exertion reflective of the global intensity of the entire session utilising Borgs scale (Borg, Hassmen, & Lagerström, 1987). Weekly diaries allowed for training relevant parameters of load, monotony and strain (Foster, 1998) to be determined.

Training load was defined as the product of duration of the session and a global measure of the perceived rate of exertion, providing a daily and weekly measure of load. Due to non-compliance from one sub-population training load, monotony and strain was subsequently excluded from analysis. Additionally, training hours were also reported. Details pertaining to average training hours prior to and in between testing phases were obtained from questionnaires at each of the testing sessions throughout the duration of the research. Average training hours were calculated for each group.

4.4.9.7 Prospective and Injury Data

In order to ascertain injury occurrence in relation to stiffness changes, participants were asked to complete a questionnaire pertaining to prior injury history within the last two years along with a customised injury report form in the event of an injury occurrence (Appendix H). A self-reporting questionnaire gathered information regarding nature of the injury, location, management and duration of time spent off training.

Athletes who did not miss or modify two consecutive training or competition sessions were defined as being injury free (uninjured) (Kirialanis et al., 2003). Only sports related lower body non-contact injuries were included in injury analysis and subsequent prediction modelling. Injured athletes were separated into two specific classification groups; 1) soft tissue and 2) overuse. Soft tissue injuries were defined as damage to muscle, ligament or tendon and included injuries such as muscle tears and strains (Sports Medicine Australia, 2010). Overuse injuries were described as injuries which occurred with a gradual onset as a result of repetitive friction, pulling, twisting or compression, this included injuries such as stress fractures/reactions, tendonitis and fasciitis (Sports Medicine Australia, 2010). Reoccurring injuries were only coded to a category once, however it was reported how many athletes presented with reoccurring injuries and no athlete presented with both a soft tissue and overuse injury. Injury incidence was reported as a percentage of the number of athletes injured total and sub-population numbers and broken down into the location of injury and injury classification.

4.5 Statistical Analyses

Normality was assessed in accordance with the critical appraisal approach (Peat & Barton, 2006) (Table 4.11). Prior to statistical analysis outliers were removed from non-normal data to ensure data was a true representation of an athletic population's stiffness profile and contributing mechanisms. Outliers were defined as scores greater than 1.5 x interquartile range as determined by Statistical Package for Social Sciences (SPSS, v21.0, Inc., Chicago, IL, USA) (Osborne & Overbay, 2004). The inclusion of the excluded outliers would significantly bias the data as the excluded data points were distinctly different to their population (Peat & Barton, 2006). Outliers were not eliminated simply based on being outliers. Following further investigation, it was identified that a previous training background may result in atypical stiffness scores. As a result, these measures were excluded from relevant tasks on the grounds that they were not a true reflection of the population characteristics. e.g. a netball athlete with previous high jump experience did not represent typical netball stiffness patterns during countermovement jump tasks.

Table 4.11- *Peat and Barton (2006) Critical Appraisal Approach.*

Checklist For Normal Distribution		
	Test	**Criterion Value**
1	Percentage differences in mean and median	Less than 10%
2	Two times the standard deviation	Less than the mean
3	Skewness	Within ± 1
4	Kurtosis	Within ± 1
5	Skewness divided by the standard error	Within ± 1.96
6	Kurtosis divided by the standard error	Within ± 1.96
7	Kolomogorov-Smirnove test	$p > 0.05$
8	Shaprio-Wilk test	$p > 0.05$

Specific statistical analysis pertaining to each study are included in the relevant section of each chapter. A summary of the statistical analysis and the relevant procedures included in this thesis are included in Table 4.12 below. All statistical analysis was undertaken using the Statistical Package for Social Sciences with an alpha level set at $p \leq 0.05$. Variables displaying p values with the range of 0.05 – 0.09 and an effect size greater than 0.50 were defined as providing a clinically meaningful difference (Cohen, 1988; Hopkins, 2005).

Table 4.12- *Overview of Statistics Utilised in Each Study.*

Study	Title	Statistical Analysis Undertaken
1	Lower body stiffness modulation strategies in well trained female athletes	One-way analysis of variance Kruskal Wallis test Pearson correlations Spearman correlations
2	Variations in lower body stiffness during sports-specific tasks in well trained female athletes	One-way analysis of variance Kruskal Wallis test Pearson correlations Spearman correlations
3	Variations in lower body stiffness modulation strategies during sports-specific tasks in well trained female athletes	One-way analysis of variance Kruskal-Wallis test Pearson correlations Spearman correlations Principal component analysis
4	Longitudinal lower body stiffness variations and associated injury risk during sports-specific tasks in well trained female athletes	Repeated measures analysis of variance Friedman test Independent t-test Mann-Whitney U Receiver operating characteristics (ROC) curve Logistic regression analysis – odds ratio

4.5.1 One-Way Analysis of Variance

One-way analysis of variance (ANOVA) was utilised to evaluate differences between the dependent variables (leg stiffness, joint stiffness, contributory kinematic mechanisms) and the explanatory variable (athletic populations). Data was checked to ensure the assumptions associated with ANOVA were not violated. These include confirming groups were statistically independent from one another, the dependent variable was normally distributed, no influential outliers existed and homogeneity of variance. Levene's test was implemented to evaluate homogeneity of variance whereby the population variance in each group is equal. In the event data violated ANOVA assumptions the equivalent non-parametric Kruskal Wallis test was implemented. Bonferrioni post-hoc analysis was utilised in order to evaluate where differences occurred between sub-populations. Additionally, effect sizes were determined for variables in accordance with the methods of Cohen's *d* to calculate the distance between mean values (m) through the units of their standard deviations (SD) (Equation 16) (Cohen, 1988). Large effect size was defined as values > 0.7, medium effect size equated to values between the range of 0.4-0.69 and small effect size was values lower than <0.39.

Equation 16

$$\frac{m1 - m2}{SD1 + SD2} \div 2$$

4.5.2 Repeated Measures Analysis of Variance

To statistically evaluate the longitudinal impact of chronic athletic training on leg stiffness ANOVA with repeated measures was utilised to assess means of participants from the same sub-population at three separate time points. Assumptions linked to repeated measures ANOVA were checked to ensure the assessed dependent variable (leg stiffness) was continuous in nature and the independent variable was from the same group. Additionally, no significant outliers distorted the mean, that data was approximately normally distributed in the evaluated variables and variance of differences within the group was equal (sphericity). Data which violated these key assumptions was analysed with the equivalent non parametric Friedman test. Similar to the one-way ANOVA statistical assessment effect sizes were determined in accordance with the methods of Cohen's *d* (Equation 16) (Cohen, 1988).

4.5.3 Independent T-Test

Independent t-tests were utilised to evaluate uninjured, injured and the two injury classification groups stiffness differences at each testing phase. Two-way analysis of variance was explored as an option to reduce error associated with multiple t-tests. However due to the limitations and violations of the assumptions associated with two-way ANOVA, utilisation of independent t-tests was required. Assumptions associated with independent t-tests were checked, these included the dependent variable is assessed on a continuous scale, the two groups are independent from each other, data did not contain significant outliers and data was approximate normal distribution for each group. In the event assumptions were violated the non-parametric Mann-Whitney U test was undertaken.

4.5.4 Correlations

Pearsons correlation coefficient was implemented to measure the strength and direction of the relationship that exists between two evaluated variables (Leg stiffness, joint stiffness and contributory measures). To ensure the statistical outcome was valid data was checked to ensure it did not violate the four associated assumptions. These include that the two variables assessed were continuous in nature and exhibit a linear relationship between the two variables. No significant outliers were present within the data and that variables were approximately normally distributed. In the event the evaluated variables violated these assumptions the equivalent non-parametric Spearman correlation was utilised. The strength of the correlation was defined by:

- Very strong- > 0.70
- Strong- 0-50 – 0.69
- Moderate- 0.30 – 0.49
- Weak- <0.30

4.5.5 Principal Component Analysis

Principal component analysis (PCA) was undertaken to provide further insight into the inferential statistical analysis evaluating joint stiffness contributions to leg stiffness. PCA is a multivariate statistical technique which allows for the investigation into the maximal amount of inter-subject variance in a data set to objectively observe differences between subject groups during the examined tasks. Variables were orthogonally transformed into uncorrelated principal components, reducing the dimensionality of the data. Leg, hip, knee and ankle stiffness scores were then inputted into a weighted PCA using the inverse variance of variables as weights. As the resultant weighted coefficient matric was not orthonormal, a transformation was undertaken to correct this. A bi-plot was then generated to allow for visually assessment of the organisation of the participant scores and orthonormal coefficients in relation to the first two principal components. MATLAB 2014a (Mathworks, Natick, MA) was utilised to calculate all PCA analysis through the available "PCA function" (for additional information see https://mathworks.com/help/stats/pca.html).

4.5.6 Receiver Operating Characteristics and Logistics Regression

In order to assess the ability of leg stiffness measures to adequately predict injury risk during sprint, anticipated change of direction and repetitive hopping tasks in athletic populations, receiver operating characteristics (ROC) curves were utilised (Peat & Barton, 2006). Due to the potential of injury incidence to effect leg stiffness values following an injury, only pre-season leg stiffness scores were assessed to predict injury risk. ROC curves were performed on three separate injury classifications, with (2) and (3) being sub-classifications of (1):

1- Injured- the presence of a lower limb injury within a season of training
2- Soft tissue- the presence of a lower limb soft tissue injury incidence
3- Overuse- the presence of a lower limb overuse injury occurrence

The ROC curve was utilised to determine a critical cut off threshold to allow for further prediction modelling. Cut off values for leg stiffness were calculated by exporting the sensitivity and specificity values. The value closest to perfect predication point (Sensitivity 0.8; 1- specificity 0.2) was deemed the critical cut off threshold (Peat & Barton, 2006) (Table 4.13). The value was then utilised to re-code data to represent participant score above or below this threshold to run the model against those coded as an injury. Soft tissue injury risk assessment was inversely coded to ensure low stiffness values indicated soft tissue injury risk. Logistic regression and odds ratio analysis was undertaken to evaluate the ability of the critical cut off threshold to accurately predict injured and non-injured athletes. Colinearity of variables using a correlation matrix was utilised.

Table 4.13- *Leg Stiffness Critical Cut Off Threshold for Logistic Regression.*

Task	Prediction Model	Leg Stiffness Cut Off Value (N/m/Kg)
	Netball	
Sprint	Injured	112.47
	Soft Tissue	109.26
	Overuse	112.00
Anticipated Change of Direction Cutting	Injured	82.12
	Soft Tissue	75.47
	Overuse	87.97
Repetitive Hopping	Injured	129.45
	Soft Tissue	128.49
	Overuse	133.72
	Endurance	
Sprint	Injured/Overuse	110.70
Anticipated Change of Direction Cutting	Injured/Overuse	112.59
Repetitive Hopping	Injured/Overuse	147.99

*No soft tissue injuries were reported for endurance athletes.

4.6 Chapter Summary

This chapter represents an overview of the generic methodological elements related to the overall research project, including research design, participant recruitment and general test procedures (data collection and analysis). The following chapters represent stand-alone studies designed to answer the specific aims of this thesis.

Chapter 5. Study 1: Lower Body Stiffness Modulation Strategies in Well Trained Female Athletes

5.1 Abstract

Lower-extremity stiffness quantifies the relationship between the amount of leg compression and the external load to which the limbs are subjected. This study aimed to assess differences in leg and joint stiffness and the subsequent kinematic and kinetic control mechanisms between athletes from various training backgrounds. Forty-seven female participants (20 nationally identified netballers, 13 high level endurance athletes and 14 age and gender matched controls) completed a maximal unilateral countermovement jump, drop jump and horizontal jump to assess stiffness. Leg stiffness, joint stiffness and associated mechanical parameters were assessed with a 10 camera motion analysis system and force plate. No significant differences were evident for leg stiffness measures between athletic groups for any of the tasks (p=0.321-0.849). However, differences in joint stiffness and its contribution to leg stiffness, jump performance outcome measures and stiffness control mechanisms were evident between all groups. Practitioners should consider the appropriateness of the task utilised in leg stiffness screening. Inclusion of mechanistic and/or more sports-specific tasks may be more appropriate for athletic groups.

KEYWORDS Leg Stiffness; Joint Stiffness; Athletic Training; Spring Mass

5.2 Introduction

Lower-extremity stiffness quantification is of importance to coaches, athletes and practitioners due to its known links to both performance and injury risk (Ambegaonkar et al., 2011; Hobara, Inoue, et al., 2010; Hobara, Kimura, et al., 2010; Laffaye et al., 2005; Toumi et al., 2004; Watsford et al., 2010). Stiffness quantifies the relationship between the amount of leg flexion and the external load to which limbs are subjected (Brughelli & Cronin, 2008a, 2008b). The spring mass model can be used to describe lower-extremity stiffness, whereby a single linear spring is compressed which controls the lowering of the body's centre of mass during ground contact (Brughelli & Cronin, 2008b; Slawinski et al., 2008). Stiffness enables the joint or limb to increase its resistance to change under an applied load, allowing for optimal storage and return of elastic energy via the stretch shortening cycle (Butler et al., 2003; Komi, 2000). By optimising lower-extremity stiffness, higher levels of elastic energy and rapid transmission of impact forces allows athletes to maximise performance (Hobara, Inoue, et al., 2010; Kuitunen, Avela, et al., 2002; Rabita et al., 2008; Slawinski et al., 2008). Leg stiffness modulation is dependent on a multitude of factors including joint stiffness and the underlying key kinematic and kinetic strategies which contributes to attenuation of leg and joint stiffness such as joint displacements, moments, touchdown angles, contact time and ground reaction forces (Arampatzis et al., 1999; Hobara, Kimura, et al., 2010; Kuitunen, Komi, et al., 2002). However, few studies have assessed stiffness and the underlying mechanisms which contribute to these potential stiffness variations between females from differing training backgrounds.

Optimal levels of leg and joint stiffness are necessary to facilitate athletic performance and reduce injury incidence, however the muscle's ability to optimise stiffness is dependent upon the capacity to produce force and the rate at which force is produced (Kuitunen, Avela, et al., 2002).Modulation of lower-extremity stiffness is reliant upon the task requirements, the individual's training status and athletic background due to physiological adaptations in neuromuscular control and co-contraction (Komi, 2000). However, an understanding of the variations in how different athletes adjust the vast array of properties that contribute to stiffness remains unclear. Further, the influence of specific, habitual training on these variations is also undetermined. As a result, it is essential to monitor the lower-extremity stiffness of athletes to gain an understanding of the mechanical strategies athletes employ in order to meet task demands.

Athletic conditioning aids in the development of the musculoskeletal system, neuromuscular control strategies, regulation of muscle activity and the overall kinematic strategies utilised by athletes

(Ambegaonkar et al., 2011; Kuitunen, Avela, et al., 2002; Kuitunen et al., 2007; Kulig et al., 2011). For example, during running, sprint athletes alter their segment kinematics through a greater range of motion at the hip joint during flexion in order to achieve maximal running speeds with little consideration for running economy (Bushnell & Hunter, 2007). Endurance runners aim to maximise running economy by incorporating minimal joint flexion and vertical oscillation of the centre of mass, resulting in an increase in leg stiffness (Bushnell & Hunter, 2007; Hobara, Kimura, et al., 2010). It appears that chronic training ultimately influences the kinematic and kinetic movement patterns of athletes, subsequently affecting the lower-extremity stiffness modulation strategies that athletes implement in order to meet task demands.

In elite sport, athlete screening and monitoring is essential to allow for early identification of injury risk and relevant implementation of preventative strategies. An increased understanding of the mechanisms which contribute to injury risk is essential. In an attempt to identify high risk athletes by profiling lower-extremity stiffness of individual athletic populations, research has primarily focused on the assessment of male athletes during basic jumping tasks. Traditional jumping tasks include maximal effort countermovement jumps, squat jumps, drop jumps or horizontal jumps (Arampatzis et al., 2004; Boullosa et al., 2011; Harrison et al., 2004; Hunter & Marshall, 2002; Moresi et al., 2011). Few studies have assessed the mechanisms that different athletic populations utilise in order to meet task demands. The investigation of differences in lower-extremity stiffness and the contributory mechanisms implemented by various athletic populations can provide an understanding of the kinematic and kinetic movement patterns employed to meet task demands. Subsequently, the assessment of the influence of various habitual training backgrounds such as high intensity, intermittent sports e.g. soccer, netball, rugby; power based training e.g. sprinting and jumping; and endurance training e.g. long distance running and triathlon, on stiffness modulation strategies is of critical importance. This is of particular necessity for female populations, who are under-reported in stiffness research and are at greater risk of injury incidence (Padua et al., 2006).

Therefore, the purpose of this study was; 1) to investigate the differences in leg and joint stiffness in different female sub-populations from varied training backgrounds, and 2) to evaluate the kinematic and kinetic mechanisms that different sub-populations use to modulate stiffness to meet task demands. It was hypothesised that during discrete jump tasks leg stiffness, joint stiffness and the contributory mechanisms would be different between sub-populations as a result of the varied training and conditioning backgrounds.

5.3 Methods

5.3.1 Experimental Approach to the Problem

This cross sectional study investigated two sub populations from varying athletic training backgrounds along with non-active control participants. The study focused on assessing unilateral stiffness of the leg spring of the participant's dominant leg, during three tasks traditionally used to assess leg stiffness. Unilateral tasks were chosen as few movement patterns in sport are performed bilaterally (Ackland et al., 2009).

5.3.2 Subjects

Forty-seven female participants (20 nationally identified netballers, 13 high level endurance athletes and 14 age and gender matched controls) volunteered to participate in this study (Table 5.1). Based on previous research assessing stiffness of athletes and non-athletes (Hobara, Kimura, et al., 2010), a large effect size (0.7) was anticipated for between-group differences for the primary variable (stiffness). Therefore, with a power level of $1- \beta = 0.8$ for F statistics (ANOVA), the minimum sample size per group was deemed to be 12 participants (Kraemer & Theimann, 1987). All athletes were injury-free at the time of testing and provided written informed consent/parental consent prior to testing, with the procedures having been approved by the Human Research Ethics Committee at the Australian Catholic University. "Injury free" was defined as not missing or modifying two consecutive training/competition sessions in the two week period prior to testing (Kirialanis et al., 2003). These populations were targeted due to their reliance on activities involving the stretch-shorten cycle and their different training and competition demands. Netballers were chosen as being representative of a high intensity intermittent sport requiring maximal jumping efforts and repeated sprints, while endurance athletes (1500m – marathon) were recruited as they are required to perform continuous, efficient running at submaximal intensity. Control group participants did not exceed four hours of weekly physical activity (Loud, Gordon, Micheli, & Field, 2005). Participants were advised to wear minimal tight clothing necessary for marker placement and their regular training shoes to reflect conditions during training and competition.

Table 5.1- *Participant Descriptive Information. Values are Mean (SD).*

Group	N	Age (Years)	Mass (kg)	Height (cm)	Average Training Hours ($h \cdot wk^{-1}$)	Training Years
Netball	20	17.4(1.5)	69.2(8.4)	178.1(5.6)	7.9(4.8)	6.4(3.6)
Endurance	13	19.7(4.0)	53.4(2.9)	165.9(4.8)	10.0(3.4)	7.5(2.5)
Control	14	22.1(2.3)	59.6(9.9)	162.9(5.5)	2.1(1.2)	-

5.3.3 Procedures

Data collection took place immediately prior to the commencement of each athletic population's competition season. Following a self-directed, whole body dynamic warm up consisting of a combination of approximately 5-10 minutes of jogging or cycling on an exercise bike followed by 10 minutes of simple dynamic, lower body mobility drills (e.g. high knees, landing and agility drills), participants were asked to complete five trials of three unilateral, lower body stiffness screening tasks; countermovement jump (CMJ), drop jump (DJ) and horizontal jump (HJ). These were classed as "traditional" stiffness assessment methods as they have been used frequently to assess leg and joint stiffness (Ambegaonkar et al., 2011; Hunter & Marshall, 2002; Kubo et al., 2007). Following a demonstration, participants performed familiarisation trials until they were comfortable with the task and displayed a continuous coordinated jump technique. In order to maintain the validity of jump data, target heights were set to ensure participants aimed to achieve maximal vertical height. Target heights were determined during familiarisation and were set at a vertical eye height greater than that achieved during practice trials. Tasks were performed on the participants' dominant leg with their hands positioned on their hips in order to minimise the contribution of arm swing to jump height and distance (Harman et al., 1990; Luhtanen & Komi, 1979). Jump order was randomised to eliminate any order effects. Leg dominance was defined using a modified protocol based on the methods of Padua et al. (2006).

5.3.3.1 Countermovement Jump

Participants were advised to raise their non-dominant leg and resume a stable single-leg stance position on the force plate. Participants were instructed to lower their centre of mass in a vertical downward motion at a self-selected pace and then perform one maximal effort jump aiming to reach maximal vertical distance from the ground. Participants were discouraged from swinging the contralateral limb. Previous research has established stiffness during CMJ task has shown good intersession reliability (CV 5.1-9.3%, ICC 0.78-0.95) (Moir & Garcia, 2009).

5.3.3.2 Drop Jump

The unilateral DJ required participants to step off a 0.40 m box, land and perform a maximal vertical jump. Participants were advised to attempt to minimise ground contact time to ensure the jump was reactive. The 0.40 m drop height was the selected as it was the most commonly reported height in previous literature assessing stiffness during this task (Ambegaonkar et al., 2011; Arampatzis et al., 1999; Arampatzis et al., 2004).

5.3.3.3 Horizontal Jump

A modified version of the Stalbom et al. (2007) HJ protocol was implemented to quantify stiffness during a basic jumping task with a horizontal component. Participants were instructed to commence the task directly behind the frame of the force plate 4.5 cm, perform a CMJ onto the plate followed by a jump aiming to achieve maximal horizontal distance. All kinematic and kinetic variables associated with stiffness during HJ task displayed good between-trial (CV 1.2-6.5%) and test-retest reliability (CV 2.26-8.28%, ICC 0.74-0.96) (Stalbom et al., 2007).

5.3.3.4 Data Collection

Kinematic data were captured using a ten camera motion analysis system sampling at 500 Hz (Vicon MX; Oxford Metrics Ltd., Oxford, United Kingdom). Kinetic data were acquired using ground mounted force plates (Advanced Mechanical Technology Inc., Watertown, U.S.A. and Kistler, 9281CA, Switzerland) sampling at 1000 Hz and covered with a Mondo track surface. Standard anthropometric measurements were determined and utilised in the standard 35 marker Vicon Plug-in-gait full body model in order to determine centre of mass displacement (COMd).

5.3.4 Data Analyses

Following analysis of the frequency content and residuals of the power spectra in kinematic data (Winter, 2005) a cut off frequency of 16 Hz was implemented in a dual, low pass, fourth order Butterworth filter. Leg and joint stiffness scores and the contributory kinematic measures were calculated using standard procedures that isolated the eccentric phase of movement and hence during the period of elastic energy storage. The eccentric phase of movement was defined as the instance of touchdown to the point where the centre of mass reached maximal vertical displacement during ground contact.

5.3.4.1 Leg and Joint Stiffness

Leg stiffness was determined using the formula presented by McMahon and Cheng (1990), whereby stiffness was calculated as the peak vertical ground reaction force (PVGRF) divided by leg length change (Equation 17). Leg length change accounted for the initial leg length of the individual, vertical displacement of the centre of mass, forward velocity at impact and contact time (CT) (Equation

18 and 19). Although traditionally the calculation of vertical stiffness is used to determine stiffness during vertical jumps such as CMJ or DJ, previous literature has established that stiffness derived using the vertical stiffness formula equates leg stiffness scores during vertical jump tasks (Butler et al., 2003). Due to the inclusion of the HJ, leg stiffness calculations were required, for consistency this method was implemented to assess each task.

Equation 17- $K_{Leg} = \frac{F_{max}}{\Delta L}$

Equation 18- $\Delta L = \Delta y + L_0(1 - cos\theta)$

Equation 19- $\theta = \sin(\frac{vT_C}{2L_0})$

Where F_{max} = peak vertical ground reaction force; ΔL = change in vertical leg length; Δy = vertical displacement of the centre of mass; L_0 = initial leg length; θ = half angle of the arc swept by the leg; v = horizontal velocity at touchdown; t_c = contact time.

For a typical representation of the individual's leg spring and contributing variables to be derived, the highest and lowest stiffness scores of the five trials were eliminated from analysis with the mean of each participant's middle three scores used for subsequent analysis (Stalbom et al., 2007). The associated joint stiffness measures and contributing mechanisms of excluded trials were removed from analysis. Leg stiffness measures were normalised to body mass and leg stiffness scores from the HJ were standardized to population specific average horizontal touch-down velocities using residual calculations derived from linear regression analysis.

Joint stiffness of the hip, knee and ankle were calculated according to the methods reported Farley et al., (1998), whereby joint stiffness is the ratio of joint moment change to angular displacement of the joint (Equation 20).

Equation 20- $K_{Joint} = \frac{\Delta J_m}{J_d}$

Where ΔJ_m= Change in joint moment from the initial point in contact to the peak joint moment during the eccentric phase of ground contact; J_d= sagittal joint displacement during the eccentric phase of ground contact.

5.3.4.2 Contributing Kinematic Mechanisms to Stiffness Modulation

The contributing kinematic and kinetic mechanisms that the different female sub-populations utilise to control stiffness to meet the tasks demands were assessed. Control mechanisms of stiffness modulation in the paper refers to the kinematic and kinetic contributions to joint stiffness and leg stiffness rather than temporal measures such as inter-segmental co-ordinations or COM motion. These control mechanism parameters included joint displacement, joint moment and touchdown angles of the hip, knee and ankle. Jump outcome performance measure of jump height was derived using the impulse method (Linthorne, 2001). Measures which contribute to jump performance including PVGRF, COMd, and CT were also assessed.

5.3.5 Statistical Analyses

Normality was assessed in accordance with a critical appraisal approach (Peat & Barton, 2006). Outliers were removed from non-normal data with a maximum of three from any one group variable, prior to statistical analysis to ensure data were a true representation of an athletic population's stiffness profile. Outliers were identified as being greater than 1.5 x Interquartile Range as determined by the Statistical Package for Social Sciences (SPSS, v21.0, Inc., Chicago, IL, USA) (Osborne & Overbay, 2004). One-way analysis of variance with Bonferroni post-hoc tests were calculated to evaluate differences in stiffness and associated modulation mechanisms for each group during the three jumping tasks. Variables which were not normally distributed or did not display homogeneity of variance were assessed using the equivalent non-parametric Kruskal-Wallis test.

Pearson correlations were calculated to assess the relationship of isolated joint stiffness contributions to the overall leg stiffness score (>0.7 very strong, 0.5-0.69 strong, 0.3-0.49 moderate) (Peat & Barton, 2006). Variables that violated correlation assumptions were assessed using Spearman correlations. All statistical analyses were evaluated using the SPSS® with an alpha level set at p≤0.05. Variables which displayed p values ranging between 0.05-0.09 and an effect size greater than 0.50 were defined as providing a clinically meaningful difference (Cohen, 1988; Hopkins, 2005).

5.4 Results

No significant differences were evident in leg stiffness measures between groups in all jump tasks (Figure 5.1). Although differences in leg stiffness measures were not evident, there were several differences at the joint level and for the contributing kinematic and kinetic control mechanisms utilised to modulate stiffness between the three groups.

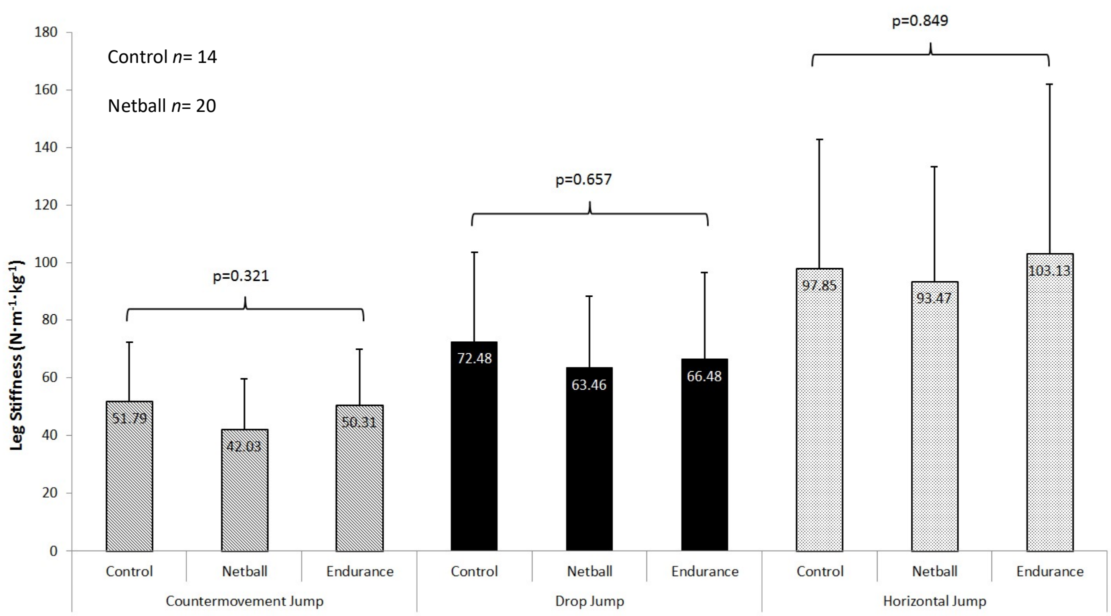

Figure 5.1- Leg stiffness differences between groups during countermovement jump, drop jump and horizontal jump. Values are means, error bars are SD.

When considering the contributing performance outcome variables for the evaluated tasks, significant differences were noted in the stiffness control mechanisms of PVGRF ($p<0.001$-0.049) and COMd ($p=0.008$-0.054) (Table 5.2). DJ contact time ($p=0.060$) indicated a clinically meaningful difference between the control and netball groups. HJ COMd also displayed a clinically meaningful difference between control and netball athletes ($p=0.065$).

Table 5.2- *Jump Performance Outcome Variables and the Contributing Kinetic Measures. Values are mean (SD).*

		Control (*n*=14)	Netball (*n*=20)	Endurance (*n*=13)	Control – Netball Effect Size	Control – Endurance Effect Size	Netball – Endurance Effect Size
CMJ	Jump Height (m)	0.09(0.03)[b]	0.15(0.04)[ac]	0.11(0.04)[b]	1.71	0.57	1.00
	PVGRF (%BW)	1.73(0.14)[b]	1.87(0.19)[ac]	1.67(0.12)[b]	0.85	0.46	1.29
	COMd (m)*	0.15(0.04)[b]	0.21(0.07)[ac]	0.15(0.04)[b]	1.09	0.00	1.09
	Jump Time (Sec)	0.845(0.228)	0.784(0.145)	0.852(0.166)	0.52	0.04	0.44
DJ	Jump Height (m)	0.06(0.02)[bc]	0.13(0.04)[ac]	0.09(0.03)[ab]	2.33	1.20	1.14
	PVGRF (%BW)*	1.73(0.17)[bc]	2.50(0.41)[a]	2.50(0.52)[a]	2.66	2.23	0.00
	COMd (m)	0.19(0.05)b	0.23(0.04)[a]	0.21(0.04)	0.89	0.44	0.50
	Contact Time (sec)	0.363(0.051)	0.449(0.110)	0.409(0.110)	1.07	0.57	0.36
HJ	PVGRF (%BW)	1.87(0.24)[bc]	2.21(0.35)[a]	2.28(0.33)[a]	1.15	1.44	0.21
	COMd (m)*	0.08(0.04)[c]	0.12(0.06)	0.13(0.06)[a]	0.80	1.00	0.17
	Contact Time (sec)	0.418(0.071)	0.414(0.075)	0.368(0.046)	0.05	0.85	0.76

[a] Significantly different to control group; [b] Significantly different to netball group; [c] Significantly different to endurance group; * Non parametric Kruskal-Wallis test implemented; Peak vertical ground reaction force (PVGRF); Centre of mass displacement (COMd); Countermovement jump (CMJ); drop jump (DJ); horizontal jump (HJ).

CMJ results established that joint stiffness differences existed between groups at the hip ($p=0.014$) and knee ($p=0.050$) (Table 5.3). On further inspection of the contributing mechanisms utilised to modulate stiffness, there were several differences between groups. These mechanistic differences included hip peak joint moment ($p<0.001$-0.001) and peak ankle moment ($p=0.010$-0.017) with knee moment trending towards a difference between control and netball populations ($p=0.069$).

The examination of correlations within each group revealed differences in contributions from joint stiffness to leg stiffness during CMJ (Table 5.3). The control group displayed a strong relationship to hip and knee stiffness, while netballers and endurance athletes displayed a relationship between leg stiffness and hip and ankle stiffness. It is important to note that the groups also displayed differences in the mechanistic contributions utilised to modulate leg stiffness to meet task demands (Table 5.3).

Table 5.3- *Differences in Kinematic Variables and their Relationship with Leg Stiffness During Countermovement Jump Assessment. Values are Mean (SD).*

CMJ	Control (*n*=14)	Control Relationship to Kleg (r)	Netball (*n*=20)	Netball Relationship to Kleg (r)	Endurance (*n*=13)	Endurance Relationship to Kleg (r)	Control – Netball Effect Size	Control – Endurance Effect Size	Netball – Endurance Effect Size
Hip Stiffness ($N\cdot m^{-1}\cdot deg^{-1}\cdot kg^{-1}$)	0.053(0.017)	0.79[d]	0.059(0.013)[c]	0.46[d]	0.043(0.014)[b]	0.58[d]	0.40	0.64	1.18
Hip Peak Joint Moment ($N\cdot m^{-1}\cdot kg^{-1}$)	1.81(0.66)[b]	0.47	2.63(0.47)[ac]	-0.54[d]	1.68(0.65)[b]	-0.28	1.43	0.20	1.67
Hip Angular Displacement (deg)	42.30(8.92)	-0.86[d]	46.53(15.28)	-0.67[d]	40.70(14.54)	-0.66[d]	0.34	0.13	0.39
Knee Stiffness ($N\cdot m^{-1}\cdot deg^{-1}\cdot kg^{-1}$)	0.014(0.006)[b]	0.59[d]	0.020(0.007)[a]	0.30	0.016(0.007)	-0.15	0.92	0.31	0.57
Knee Peak Joint Moment ($N\cdot m^{-1}\cdot kg^{-1}$)	1.09(0.29)	0.02	1.45(0.50)	0.10	1.10(0.45)	-0.15	0.88	0.03	0.74
Knee Angular Displacement (deg)	50.78(6.79)	-0.76[d]	57.07(13.71)	-0.50[d]	52.29(11.00)	-0.66[d]	0.58	0.17	0.38
Ankle Stiffness ($N\cdot m^{-1}\cdot deg^{-1}\cdot kg^{-1}$)	0.074(0.034)	0.33	0.070(0.024)	0.67[d]	0.056(0.036)	0.78[d]	0.14	0.51	0.46

CMJ	Control (*n*=14)	Control Relationship to Kleg (r)	Netball (*n*=20)	Netball Relationship to Kleg (r)	Endurance (*n*=13)	Endurance Relationship to Kleg (r)	Control – Netball Effect Size	Control – Endurance Effect Size	Netball – Endurance Effect Size
Ankle Peak Joint Moment ($N{\cdot}m^{-1}{\cdot}kg^{-1}$)	1.48(0.38)[b]	0.36	1.88(0.30)[ac]	0.40	1.43(0.51)[b]	0.53	1.17	0.11	1.08
Ankle Angular Displacement (deg)	18.12(4.47)	-0.34	21.44(4.75)	-0.42	19.40(6.27)	-0.56	0.72	0.24	0.37

[a] Significantly different to control group; [b] Significantly different to netball group; [c] Significantly different to endurance group; [d] Significant correlation ($p<0.05$).

Similar to the CMJ results, the DJ examination revealed several significant differences in the methods used to modulate stiffness (Table 5.4). Between-group differences included peak hip moment (p=0.005), peak ankle moment (p=0.050), hip touchdown angle (p=0.002-0.012), knee touchdown angle (p=0.003) and ankle touchdown angle (p=0.022). Further, peak hip moment between control and endurance athletes (p=0.080) and knee angular displacement between control and netball athletes (p=0.092) yielded clinically meaningful differences.

In further congruence with the CMJ results, the DJ results displayed differences in the mechanistic contributions utilised by each group to modulate leg stiffness to meet task demands (Table 5.4). Assessment of joint contributions during DJ's in the control population established that knee and ankle stiffness had a very strong relationship with leg stiffness. Results revealed that leg stiffness of netball athletes was related to hip, knee and ankle stiffness, while hip and ankle stiffness were strongly related in the modulation of leg stiffness for endurance athletes during this high impact jump task.

Table 5.4- *Differences in Kinematic Variables and their Relationship with Leg Stiffness During Drop Jump Assessment. Values are Mean (SD).*

DJ	Control (*n*=14)	Control Relationship to Kleg (r)	Netball (*n*=20)	Netball Relationship to Kleg (r)	Endurance (*n*=13)	Endurance Relationship to Kleg (r)	Control – Netball Effect Size	Control – Endurance Effect Size	Netball – Endurance Effect Size
Hip Stiffness ($N \cdot m^{-1} \cdot deg^{-1} \cdot kg^{-1}$)*	0.056(0.084)	-0.02	0.082(0.058)	0.62[d]	0.136(0.159)	0.71[d]	0.36	0.63	0.45
Hip Peak Joint Moment ($N \cdot m^{-1} \cdot kg^{-1}$)*	1.94(1.06)[b]	-0.17	3.00(0.81)[a]	0.46d	3.17(1.89)	0.77[d]	1.12	0.80	0.12
Hip Angular Displacement (deg)*	19.53(8.92)	-0.71[d]	21.87(8.99)	-0.71[d]	19.25(6.00)	-0.80[d]	0.26	0.07	0.34
Hip Touchdown Angle (deg)*	14.96(9.01)[bc]	-0.11	22.54(7.55)[a]	-0.08	24.81(3.24)a	-0.16	0.91	1.45	0.39
Knee Stiffness ($N \cdot m^{-1} \cdot deg^{-1} \cdot kg^{-1}$)	0.063(0.031)	0.77[d]	0.065(0.022)	0.78[d]	0.050(0.029)	-0.08	0.07	-0.43	0.58
Knee Peak Joint Moment ($N \cdot m^{-1} \cdot kg^{-1}$)	2.08(0.90)	0.74[d]	2.39(0.78)	0.55[d]	1.83(1.09)	-0.30	0.37	-0.25	0.59
Knee Angular Displacement (deg)	43.70(9.88)	-0.60[d]	50.45(7.92)	-0.79[d]	45.69(8.33)	-0.71[d]	0.75	0.22	0.59

DJ	Control (*n*=14)	Control Relationship to Kleg (r)	Netball (*n*=20)	Netball Relationship to Kleg (r)	Endurance (*n*=13)	Endurance Relationship to Kleg (r)	Control – Netball Effect Size	Control – Endurance Effect Size	Netball – Endurance Effect Size
Knee Touchdown Angle (deg)	10.91(4.83)[b]	0.40	16.00(4.14)[a]	0.18	14.43(3.24)	-0.11	1.13	0.86	0.42
Ankle Stiffness ($N \cdot m^{-1} \cdot deg^{-1} \cdot kg^{-1}$)*	0.044(0.013)	0.77d	0.052(0.013)	0.74[d]	0.054(0.030)	0.62[d]	0.62	0.43	0.09
Ankle Peak Joint Moment ($N \cdot m^{-1} \cdot kg^{-1}$)*	2.31(0.63)[b]	-0.60[d]	2.71(0.57)[a]	0.72[d]	2.65(1.47)	0.54[d]	0.67	0.30	0.05
Ankle Angular Displacement (deg)*	54.60(5.65)	-0.33	55.78(4.46)	-0.41	53.00(9.27)	-0.26	0.23	0.21	0.38
Ankle Touchdown Angle (deg)	-34.67(6.38)[c]	0.32	-30.72(6.84)	-0.03	-26.94(7.34)a	0.22	0.58	1.12	-0.53

[a] Significantly different to control group; [b] Significantly different to netball group; [c] Significantly different to endurance group; d Significant correlation ($p<0.05$); * Non parametric Kruskal-Wallis test implemented; – negative ankle touchdown angles indicates plantar-flexion.

The HJ results revealed significant differences in contributing modulation strategies between groups (Table 5.5). At the joint level, knee stiffness was different ($p<0.001$-0.016), while ankle stiffness yielded a clinically meaningful difference between endurance and netball athletes ($p=0.063$). Mechanistic variables contributing to stiffness modulation revealed several differences between groups including peak ankle moment ($p=0.014$-0.020) and peak knee joint moment ($p=0.012$). Furthermore, ankle angular displacement ($p=0.092$) displayed a clinically meaningful difference between control and endurance groups.

During the HJ, control and endurance groups displayed a very strong relationship between hip stiffness and leg stiffness, while netball athletes had very strong contributions from ankle stiffness. Similar to the CMJ and DJ, results of the HJ established that each group utilised different joint stiffness and mechanistic contributions to modulate leg stiffness to meet task demands.

Table 5.5- *Differences in Kinematic Variables and their Relationship with Leg Stiffness During Horizontal Jump Assessment. Values are Mean (SD).*

HJ	Control (*n*=14)	Control Relationship to Kleg (r)	Netball (*n*=20)	Netball Relationship to Kleg (r)	Endurance (*n*=13)	Endurance Relationship to Kleg (r)	Control – Netball Effect Size	Control – Endurance Effect Size	Netball – Endurance Effect Size
Hip Stiffness ($N \cdot m^{-1} \cdot deg^{-1} \cdot kg^{-1}$)*	0.203(0.136)	0.72[d]	0.135(0.086)	0.20	0.176(0.228)	0.71d	0.60	0.14	0.24
Hip Peak Joint Moment ($N \cdot m^{-1} \cdot kg^{-1}$)	2.06(0.55)	0.13	1.76(0.85)	-0.20	2.40(0.95)	0.14	0.42	0.44	0.71
Hip Angular Displacement (deg)	11.41(7.23)	-0.64[d]	11.04(4.35)	-0.06	10.09(6.47)	-0.52	0.06	0.19	0.17
Hip Touchdown Angle (deg)	39.57(16.86)	0.45	47.78(8.39)	0.49d	46.61(10.17)	0.29	0.62	0.51	0.13
Knee Stiffness ($N \cdot m^{-1} \cdot deg^{-1} \cdot kg^{-1}$)*	0.029(0.027)[bc]	-0.29	0.099(0.065)[a]	0.41	0.066(0.040)[a]	-0.28	1.41	1.08	0.61
Knee Peak Joint Moment ($N \cdot m^{-1} \cdot kg^{-1}$)	0.816(0.597)[b]	-0.01	1.788(0.849)[a]	-0.34	1.420(1.176)	-0.12	1.32	0.65	0.36
Knee Angular Displacement (deg)	26.97(16.87)	-0.78[d]	28.21(11.77)	-0.76[d]	31.39(8.90)	-0.77[d]	0.09	0.33	0.30
Knee Touchdown Angle (deg)	27.86(14.58)	0.59d	32.62(10.00)	0.62[d]	25.30(7.23)	0.47	0.38	0.22	0.84
Ankle Stiffness ($N \cdot m^{-1} \cdot deg^{-1} \cdot kg^{-1}$)*	0.099(0.039)	0.27	0.119(0.047)	0.59[d]	0.094(0.047)	0.04	0.46	0.12	0.53

HJ	Control (*n*=14)	Control Relationship to Kleg (r)	Netball (*n*=20)	Netball Relationship to Kleg (r)	Endurance (*n*=13)	Endurance Relationship to Kleg (r)	Control – Netball Effect Size	Control – Endurance Effect Size	Netball – Endurance Effect Size
Ankle Peak Joint Moment ($N\cdot m^{-1}\cdot kg^{-1}$)	1.73(0.51)[bc]	-0.11	2.39(0.53)[a]	0.19	2.50(0.92)[a]	0.45	1.27	1.04	0.15
Ankle Angular Displacement (deg)*	19.96(9.23)	-0.26	23.91(10.81)	-0.32	28.16(12.60)	-0.04	0.39	0.74	0.36
Ankle Touchdown Angle (deg)*	7.21(8.39)	-0.37	7.57(9.98)	-0.05	4.79(13.57)	0.16	0.04	0.21	0.23

a Significantly different to control group; b Significantly different to netball group; c Significantly different to endurance group; d Significant correlation ($p<0.05$); * Non parametric Kruskal-Wallis test implemented.

5.5 Discussion

The present study evaluated leg stiffness, joint stiffness and the contributing kinematic stiffness modulation strategies that female athletic populations employ during basic jumping tasks. It was hypothesised that differences in leg stiffness, joint stiffness, contributing kinematic mechanisms and performance would be evident due to the impact of varying quantity and styles of training on movement. Although leg stiffness did not differ between participants during the jump tasks, a range of differences in joint contributions and the underlying kinematic movement strategies utilised to modulate leg and joint stiffness to meet varying task demands were evident between groups.

The results revealed no overall leg stiffness differences between groups. It was anticipated that leg stiffness differences would be evident due to variances in strength, co-ordination, co-contraction, neuromuscular control and intrinsic properties of muscle fibres unique to each athletic training background. Although not evident in this study, previous research has established that differences in leg stiffness measures exist during more dynamic tasks such as repetitive hopping between control and endurance populations (Hobara, Kimura, et al., 2010). As the tasks in the present study were discrete maximal efforts, the simplistic nature of these tasks may not induce the need for higher levels of stiffness in relatively lower loading tasks for highly trained athletes when the movement patterns may not specifically reflect high impact loading associated with an athlete's training or competition. The results indicated clear differences at the joint level in the underlying control mechanisms utilised to modulate lower-extremity stiffness between groups, despite there being no discernible change in leg stiffness. This suggests that discrete maximal effort jump tasks which have traditionally been utilised to assess stiffness may lack the sensitivity necessary to discriminate between groups of differing training abilities.

The CMJ task represents a relatively low load, power-based task. As leg stiffness and its associated neural control strategies are dependent on the assessed task (Komi, 2000) and influenced by an individual's training background, it follows that athletes who engage in regular vertical jump movement patterns, such as netballers, would modulate stiffness in a different manner. The results established that netball athletes, despite no differences in leg stiffness, displayed greater jump heights, likely achieved through greater joint stiffness, higher PVGRFs, larger COMd, and higher peak moments at the hip, knee and ankle (Tables 5.2 and 5.3). This suggests netballers more effectively optimise leg stiffness through enhanced contributions of joint stiffness and appropriate utilisation of kinematic joint control strategies resulting in superior jump performance. Varying stiffness modulation strategies observed between groups performing the same task may be attributed to differing intrinsic muscle fibre types, pre-activation and neuromuscular control, known to be developed through training and unique to each athletic population (Hobara et al., 2008; Hobara, Kimura, et al., 2010). This was further evident in the observed differences between athletic populations and the control group in the joint contributions used to modulate leg stiffness to meet CMJ task demands (Table 5.3). The inability of traditional discrete maximal jump tasks to detect leg stiffness differences between groups, despite clear control mechanism differences, suggests that mechanism measures during discrete tasks need to be assessed. Alternatively, potentially more sensitive, dynamic sport-specific tasks should be utilised when screening an athlete's leg stiffness from a performance or injury perspective.

Both of the athletic groups assessed in the current study are regularly exposed to repeated high impact loads in their daily training environment, resulting in neural and physiological adaptations to such stimuli (Butler et al., 2003; Komi, 2000; Rabita et al., 2008; Toumi et al., 2004). The DJ task, frequently utilised to evaluate stiffness, assesses higher load impacts, potentially more aligned to athletic adaptations. Although no discernible between group leg stiffness differences were evident, both athletic sub-populations appeared to utilise stiffness more effectively to achieve superior jump performance, with athletes displaying greater jump heights. Greater jump heights appeared to be due to higher PVGRF and altered kinematic body geometry, with both athletic groups displaying higher degrees of hip flexion angles at touchdown (Tables 5.2 and 5.4). Higher hip flexion angles may allow for more efficient ground contact, optimal mechanical power output (Kuitunen et al., 2007; Kuitunen et al., 2011) and optimal propulsion (Williams, 2000) leading to greater PVGRFs essential for the optimal storage of elastic energy (Butler et al., 2003; Komi, 2000). In addition, netball athletes achieved greater jump heights and displayed more leg compression during ground contact (greater COMd), probably due to greater angular displacement at the knee (Table 5.4). These joint control strategies reflect the training and competition demands of this population where athletes are required to achieve maximal jump height, consequently impacting on the kinematic strategies utilised. In contrast, the control group appeared to approach landing with a significantly more extended, "rigid" leg in anticipation for impact and appeared to lack the necessary strength to maintain limb rigidity. As a result, controls displayed similar joint displacements and COMd to the athletic groups, along with lower PVGRFs and lower peak joint moments at the hip and ankle. This resulted in lower jump heights, potentially reflecting reduced ground contact effectiveness.

During the DJ task correlation results between joint and leg stiffness suggests that modulation strategies differed between groups, with netball athletes appearing to employ a 'simple spring' mechanism with all assessed lower body joints contributing to leg stiffness control. Conversely, endurance athletes predominantly modulated leg stiffness through hip and ankle stiffness, whilst control participants relied upon knee and ankle stiffness contributions to meet DJ task demands. These contrasts in lower limb kinematics and kinetics further emphasise the concept that various stiffness modulation strategies exist at the joint level within the assessed sub-populations, despite an absence of differences in leg stiffness. Such differences are thought to reflect sport-specific training and competition adaptions.

The only maximal jump task incorporating horizontal movement (HJ), displayed similar results to the vertical jump tasks, whereby differences were identified in the kinetic and kinematic control mechanisms utilised between the sub-populations. In the sporting realm few movement patterns require solely vertical movements. Since stiffness modulation is dependent on the task demands (Komi, 2000), it is not surprising that differences were evident in the modulation strategies utilised between athletic populations, particularly endurance athletes and the control group during a task requiring horizontal movement. These differences included higher PVGRF, COMd, knee stiffness, ankle angular displacement and peak ankle moment (Table 5.5). Chronic training influences the kinetic and kinematic strategies of athletes to meet task demands (Bushnell & Hunter, 2007; Hobara, Kimura, et al., 2010). For example, when considering sprinting; a task relevant to netball and endurance athletes; a stiffer knee joint is advantageous in achieving a shorter ground contact and higher mechanical efficiency (Kuitunen, Komi, et al., 2002). It can be speculated that higher ratios of joint stiffness are achieved in athletic groups as training is known to influence the neuromuscular adaptations and resultant joint strategies (Arampatzis et al., 1999; Kuitunen, Komi, et al., 2002). Accordingly, athletes appear to employ control mechanisms reflective of their training background. Although there were clear differences at the joint level between control and endurance groups, hip stiffness was a key contributor to stiffness modulation for both groups. Alternatively, netball athletes appeared more reliant upon contributions of ankle stiffness to aid the modulation of leg stiffness. Accordingly, netball athletes displayed higher levels of ankle stiffness to meet task demands when compared to the endurance group, who relied upon different joint control strategies relevant to their training background.

The present study was one of the few studies to assess female participants from varying training backgrounds. It is known that females display the highest rates of injury incidence and lower levels of stiffness when compared to their male counterparts (Padua et al., 2006) and as a result it is important to understand stiffness and the underlying mechanisms which contribute to stiffness modulation. It was evident that traditional maximal jumping tasks were unable to identify leg stiffness differences between groups despite clear variations in key kinematic and kinetic mechanisms which contribute to stiffness control. This was further supported through the key joint contributions to leg stiffness, whereby athletic groups utilised stiffness contributions of one key joint across each of the assessed tasks. For netball athletes, ankle stiffness was the main contributor, while endurance athletes appeared to utilise the contribution from the hip to modulate leg stiffness. It follows that netball athletes may display ankle-dominant strategies during all assessed tasks as a stiffer ankle is essential in running and jumping movements (Arampatzis et al., 1999; Hobara, Kimura, et al., 2010). These movement patterns are specific to the training and competition demands of this population and as a result may play an influential role in contributory joint control strategies. The use of the hip joint as a key contributor to leg stiffness modification in endurance trained athletes may reflect the important role this joint has in generating running velocity (O'Meara & Moresi, 2012). Unlike the athletic groups the control population displayed no common contributing joint across any of the three tasks, which may reflect the absence of any specific training capacity. It can be suggested that different athletic groups employ a variety of modulation strategies, specific to each population in order to meet task demands which are likely based upon neuromuscular adaptations to training. The control group did not appear to have consistent contributions from any particular joint across all tasks, suggesting that non-active individuals do not have a clear modulation strategy to meet task demands. These differences highlight the importance of utilising sport-specific assessment activities and identifying the mechanism contributions when screening athletes as they may be more appropriate in the evaluation of leg stiffness differences between specific populations. The present study is one of the few studies to investigate leg stiffness in high level female athletes from differing sporting backgrounds. Whilst investigation of high level athletes is a strength of the study, it is acknowledged that the relatively limited number of available, uninjured high level athletes within these specific populations may challenge the statistical power of the present study. Despite this potential limitation, the findings appear clear and consistent across the varied tasks investigated. Another notable strength of the study was the inclusion of a multitude of tasks assessed across multiple high level athletic disciplines, creating a profile of how differing athletic populations modulate stiffness to meet varying task demands.

5.6 Practical Applications

The results of this study identified variations in leg stiffness control strategies, joint stiffness and joint contributions between different female sub-populations. It would appear that leg stiffness assessment during basic maximal jumping tasks lacks adequate sensitivity to identify these modulation differences between groups with varying habitual training backgrounds. The results provide empirical evidence suggesting that appropriate monitoring tasks must be given due attention to assess stiffness from a performance or injury perspective within athletic populations. It may be more beneficial to screen athletes through dynamic and functional tasks relevant to an athlete's habitual training background or the inclusion of assessments of contributing mechanisms. If screening tools are utilised that do not consider an athlete's training background, the results may not represent an athlete's typical leg stiffness during their training and competition phases, therefore potentially masking any relationship to injury risk or performance. Accordingly, practitioners screening for lower limb stiffness differences with a view to determining performance capacity or injury risk should consider utilising sports-specific tests or assessing the contributory stiffness mechanisms.

5.7 Acknowledgments

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5.8 Summary and Key Findings

Chapter 5 highlighted that basic maximal effort jumping tasks traditionally utilised to assess stiffness of the lower limb appear to lack the necessary sensitivity to discriminate differences between populations from varied training backgrounds. Therefore, it may be inappropriate to use basic jumping tasks in athlete screening and monitoring in the assessment of stiffness from a performance and injury perspective. As clear stiffness modulation differences appear evident between varying athletic populations, it may be more beneficial to screen athletes through dynamic tasks relevant to an athletes' training background.

5.9 Recommendations for Future Research

There is a need to evaluate lower-extremity stiffness and the associated modulation strategies athletes utilise during dynamic and sports-specific tasks relevant to an athletes' habitual training background. Assessment of leg stiffness, joint stiffness and their contributory mechanisms during tasks which reflect typical training and competition stiffness characteristics may provide understanding for coaches, practitioners and researchers on ways to enhance performance and minimise injury incidence. Utilisation of screening tools with little consideration of relevance to an athlete's training background may not represent typical training and competition stiffness properties, potentially concealing relevant information to injury risk or performance.

5.10 Importance of Chapter 6

As identified by the results of Chapter 2, 3 and 5 few studies have evaluated leg stiffness during tasks relevant to an athlete's training background. Therefore, there is a need to investigate leg stiffness during dynamic and sports-specific tasks. Additionally, identification of appropriate monitoring tools for athlete screening and monitoring is warranted to enhance practical application of findings in high performance sport.

Chapter 6 evaluated Aim 2 of the thesis:

Aim 2 – To investigate differences in leg stiffness in different female sub-populations from varied training backgrounds during dynamic and sports-specific tasks. Further, to evaluate the performance variables which contribute to leg stiffness. Additionally, to assess the relationship between stiffness during dynamic jumping and sports-specific tasks.

Chapter 6. Study 2: Variations in Lower Body Stiffness During Sports-Specific Tasks in Well-Trained Female Athletes

6.1 Abstract

The present study aimed to assess the differences in leg stiffness and the associated performance variables between athletes from various training backgrounds during tasks relevant to athletic training. Forty-seven female participants (20 nationally identified netballers, 13 high level endurance athletes and 14 age and gender matched controls) completed a sprint, anticipated sidestep change of direction and unilateral repetitive hopping task to assess leg stiffness and the relationship of stiffness between the different tasks. Leg stiffness and performance variables were evaluated with a 10 camera motion analysis system and force plate. Significant differences were evident in leg stiffness and the contributing performance variables between groups across all assessed tasks ($p<0.001$-0.017). Furthermore, results indicated that the control group displayed no leg stiffness relationship between the evaluated tasks, while the stiffness relationship between tasks within athletic populations reflected training specific demands of athletes. Differences in the way that groups optimize leg stiffness suggests that functional tasks may be superior screening tests to discriminant stiffness differences between groups.

KEYWORDS Leg stiffness; athletic training; sprinting; change of direction; hopping.

6.2 Introduction

Stiffness of the leg spring quantifies the relationship between the amount of leg flexion and the external load to which limbs are subjected (Brughelli & Cronin, 2008a, 2008b). This phenomenon can be described through the spring-mass model, where the leg 'spring' is compressed through the lowering of the centre of mass during ground contact (Brughelli & Cronin, 2008b; Slawinski et al., 2008). Optimizing stiffness allows the joint or limb to resist change under an applied load, maximising the muscles force output during the stretch shortening cycle (Butler et al., 2003; Komi, 2000). Higher levels of elastic energy and rapid transmission of ground reaction forces allow athletes to achieve maximal performance (Hobara, Inoue, et al., 2010; Kuitunen, Avela, et al., 2002; Rabita et al., 2008; Slawinski et al., 2008). Few studies have assessed the optimal stiffness necessary to meet the demands of tasks relevant to sport and the potential stiffness variations between females from differing training backgrounds.

Stiffness is linked to both performance and injury risk (Ambegaonkar et al., 2011; Comyns et al., 2007; Hobara, Inoue, et al., 2010; Hobara, Kimura, et al., 2010; Laffaye et al., 2005; Watsford et al., 2010), where higher levels of stiffness are associated with an elevated risk of overuse, bone related injuries (Butler et al., 2003; Hobara, Kimura, et al., 2010). Additionally, lower levels of stiffness are suggested to be related to soft tissue injury risk (Butler et al., 2003). It has been suggested that an athlete's training background may be associated with an increased risk of specific types of injury incidence (Comyns et al., 2007; Hobara, Kimura, et al., 2010; Laffaye et al., 2005). To facilitate athlete performance and minimization of injury incidence, optimization of stiffness is necessary and dependent on the muscle's ability to modulate stiffness, force production, absorption and rate at which force is produced (Butler et al., 2003). Stiffness modulation is reliant upon the task requirements, the individual's training status and athletic training background of individuals (Komi, 2000). However, an understanding of the variations in how different athletic populations optimize stiffness to meet the demands of sport specific tasks remains unclear. It is essential to monitor stiffness to gain an understanding of the implications for performance enhancement and injury risk minimization.

Although the optimal leg stiffness relationship to sporting demands is unclear, research indicates that athletic training aids in the development of key stiffness control variables, including the musculoskeletal system, neuromuscular control, co-contraction and regulation of muscle activity (Ambegaonkar et al., 2011; Kuitunen, Avela, et al., 2002; Kuitunen et al., 2007; Kuitunen et al., 2011).

Chronic training also influences the kinematic and kinetic strategies utilized by athletes, subsequently affecting lower limb stiffness modulation and optimization that athletes employ to meet task demands (Bushnell & Hunter, 2007; Hobara, Kimura, et al., 2010). In order to profile optimization of stiffness between diverse athletic populations, research has primarily focused on the assessment of stiffness during discrete jumping tasks such as maximal countermovement jumps and drop jumps (Ambegaonkar et al., 2011; Arampatzis et al., 2004; Hunter & Smith, 2007). Recent research has suggested these tasks lack the adequate sensitivity to discriminate stiffness differences between athletic groups and appear unrelated to stiffness measures derived from sports-specific tests (Millett, Moresi, Watsford, Taylor, & Greene, 2013; Millett et al., 2015; Millett, Moresi, Watsford, Taylor, & Greene, 2016). This brings into question the appropriateness of these tests as a daily monitoring tool for athletes, given they may not reflect an athlete's typical stiffness during training or competition. Investigation of stiffness and the contributory mechanisms athlete's utilize to meet the performance demands of sports-specific tasks relevant to athletic training and conditioning is needed.

Athlete screening and monitoring is essential in elite sport to allow for early identification of injury risk and relevant implementation of preventative strategies. To identify high risk athletes through lower limb stiffness profiling, research has generally focused on assessing male athletes during basic jumping tasks (Arampatzis et al., 2004; Boullosa et al., 2011; Harrison et al., 2004). However, recent research suggests basic jumping tasks such as countermovement jump and drop jump may lack adequate sensitivity to distinguish differences between athletes from varied training backgrounds (Millett et al., 2015). Further, in netball athletes it would appear stiffness elicited during countermovement jumps traditionally utilized to assess stiffness does not represent typical leg stiffness during sports-specific tasks relevant of athletic training and competition background (Millett et al., 2013; Millett et al., 2015). It is essential that appropriate monitoring tasks are implemented to evaluate stiffness from a performance and injury perspective and that tests are efficient and reflective of stiffness levels present during the daily training environment. Although it appears links exist between repeat jumps and functional stiffness measures, it is unclear if this task is relevant as a screening method for athletes. Subsequently, the assessment and identification of tasks which reflect stiffness levels during an athlete's training and competition environment is of critical importance. This is of particular necessity for female populations who are at greater risk of injury occurrence (Padua et al., 2006).

Therefore, the purpose of this study was; 1) to investigate the differences in leg stiffness in different female sub-populations from varied training backgrounds during dynamic and sports-specific tasks, 2) to evaluate the performance variables which contribute to leg stiffness differences, and 3) to assess the relationship between stiffness during dynamic jumping tasks and sports-specific tasks. It was hypothesized that during dynamic reactive jump tasks and sports-specific tests leg stiffness and variables which contribute to stiffness would differ between sub-populations as a result of varied training and conditioning backgrounds. It was also theorized that dynamic reactive jumping tasks may provide an adequate relationship to sports-specific tests.

6.3 Methods

6.3.1 Experimental Approach to the Problem

A cross sectional study design assessed two sub populations from different athletic training backgrounds along with non-active control participants. The focus of this study was to assess the stiffness of the leg spring in the participant's dominant leg and the relationship of leg stiffness measures between three tasks reflecting dynamic and sports-specific movements.

6.3.2 Subjects

Based on research assessing stiffness of athletes (Hobara, Kimura, et al., 2010), a moderate-large between group difference was expected in the current study. To ensure sufficient statistical power (1-β = 0.8) a priori power analysis for F statistics (ANOVA) revealed that at least 12 participants were required in each group. A total of 47 female participants (20 nationally identified netballers, 13 high level endurance athletes and 14 age matched controls) volunteered to participate in the study (Table 6.1). Testing procedures were approved by the Human Research Ethics Committee of the Australian Catholic University. All participants provided written informed consent/parental consent and were injury free at time of testing. Injury free was defined as not missing or modifying two consecutive training or competition sessions in the two week period prior to testing (Kirialanis et al., 2003). These populations were identified due to different training and competition demands and their reliance on activities involving the stretch-shortening cycle. Netball athletes were identified as being representative of a high intensity, intermittent sport requiring maximal jumping efforts, explosive sprints and change of direction, while endurance athletes (1500m – marathon) were targeted as their training demands require them to perform continuous running at submaximal intensity with optimal efficiency. Control group participants did not exceed four hours of weekly physical activity.

Table 6.1- *Participant Descriptive Information. Values are Mean (SD).*

Group	N	Age (Years)	Mass (kg)	Height (cm)	Average Training Hours (h/wk)	Training Years
Netball	20	17.4 (1.5)	69.2 (8.4)	178.1 (5.6)	7.9 (4.8)	6.4 (3.6)
Endurance	13	19.7 (4.0)	53.4 (2.9)	165.9 (4.8)	10.0 (3.4)	7.5 (2.5)
Control	14	22.1 (2.3)	59.6 (9.9)	162.9 (5.5)	2.1 (1.2)	-

6.3.3 Testing Procedures

Data collection took place immediately prior to the commencement of each athletic population's competition season. Participants performed a standardized warm up, prior to completing five trials of three different tasks reflective of dynamic movements in the daily training environment; a sprint, anticipated sidestep cutting and repetitive hopping. Following a demonstration, participants performed familiarization trials until they were comfortable with the task and displayed a continuous coordinated movement. Task order was randomized to eliminate any order effects, with the exception of the repetitive hopping task which was performed last to ensure fatigue did not bias results. All tasks were performed on the participant's dominant leg. Leg dominance was defined using a modified protocol based on the methods of Padua et al. (2006).

6.3.3.1 Sprint

Participants performed a 40 meter sprint at their event competition pace. To ensure trials imitated movement patterns of the daily training environment, participants were discouraged from decelerating or overextending to strike the plates. Trials which reflected these qualities were classed as unsuccessful.

6.3.3.2 Anticipated Sidestep Cutting

The anticipated cutting task was selected as high intensity intermittent sporting populations are required to perform sharp change of direction cutting movements. Participants were instructed to approach the cut with a speed representative of competition pace. The task required participants to land and push diagonally sideways with the subsequent stride of the non-dominant leg landing between 30-40 degrees relative to the direction of the contact point of the dominant leg. This angle represented a directional change in game situations established in previous literature (McLean et al., 2004).

6.3.3.3 Repetitive Hopping

This task provided a representation of a dynamic jump tasks as an intermediate movement pattern between basic jump tasks and sport specific movements. Participants were asked to perform 27 continuous, reactive hops at a self-selected submaximal intensity; the first five and last two trials were excluded from analysis with the mean of the remaining trials included in subsequent evaluation (Moresi et al., 2014). To ensure the repeatability and reliability of jump data, target vertical eye heights were set at 70% of maximal jump height representative of submaximal intensity. Target height was determined from familiarization trials once participants were able to demonstrate a continuous coordinated jump technique. Tasks were performed on the participants' dominant leg with their hands positioned on their hips in order to minimize the contribution of arm swing to jump height (Harman et al., 1990; Luhtanen & Komi, 1979).

6.3.3.4 Data Collection

A ten camera motion analysis system sampling at 500 Hz (Vicon MX; Oxford, United Kingdom) was used to capture kinematic data. Kinetic data was acquired using ground mounted force plates (Advanced Mechanical Technology Inc., Watertown, U.S.A. or Kistler, 9281CA, Switzerland) sampling at 1000 Hz and covered with a Mondo track surface. Standardized anthropometric measures were utilized in the standard Vicon Plug-in-gait full body model (Vicon; Oxford, United Kingdom) in order to determine centre of mass displacement (COMd).

6.3.4 Data Analyses

Following analysis of the frequency content and residuals of the power spectra in kinematic data (Winter, 2005), a cut off frequency of 23 Hz for sprint and sidestep cutting and 16 Hz for repetitive hopping was implemented in a dual, low pass, fourth order Butterworth filter. Leg stiffness measures were isolated to the eccentric phase of movement where elastic energy storage occurs. Eccentric phase of movement was defined at the instance of touchdown to the point where the centre of mass reached maximal vertical displacement during ground contact.

6.3.4.1 Leg Stiffness

Stiffness of the leg spring was determined using the formula presented by McMahon and Cheng (1990). Leg stiffness equates to the peak vertical ground reaction force (PVGRF) divided by leg length change. Change in leg length takes into account the initial leg length of the individual, vertical displacement of the centre of mass, horizontal velocity at impact and contact time (CT). Traditionally vertical stiffness calculations are utilized to assess stiffness during vertical jumps such as repetitive hopping (Brughelli & Cronin, 2008b). However, as leg stiffness calculations were required to assess stiffness during sprint and sidestep cutting tasks, the leg length change method was utilized to incorporate consistency in the evaluation of each task. Previous literature has established that during vertical jump tasks, stiffness determined through vertical stiffness calculations equates to scores derived through leg stiffness formulas (Butler et al., 2003).

To ensure a typical representation of the individual's leg spring during the sprint and sidestep cutting tasks, the highest and lowest stiffness scores of the five trials were eliminated from analysis with the mean of each participant's middle three scores used in subsequent evaluation (Stalbom et al., 2007). Leg stiffness measures were normalized to body mass and standardized to the average horizontal touchdown velocity (sprint and cutting tasks) or jump frequency (repeat jump task) for all participants using residual calculations derived from population specific linear regression analysis. Individual population residual calculations were utilized due to variations in the linear regression slopes between groups (Figure 6.1).

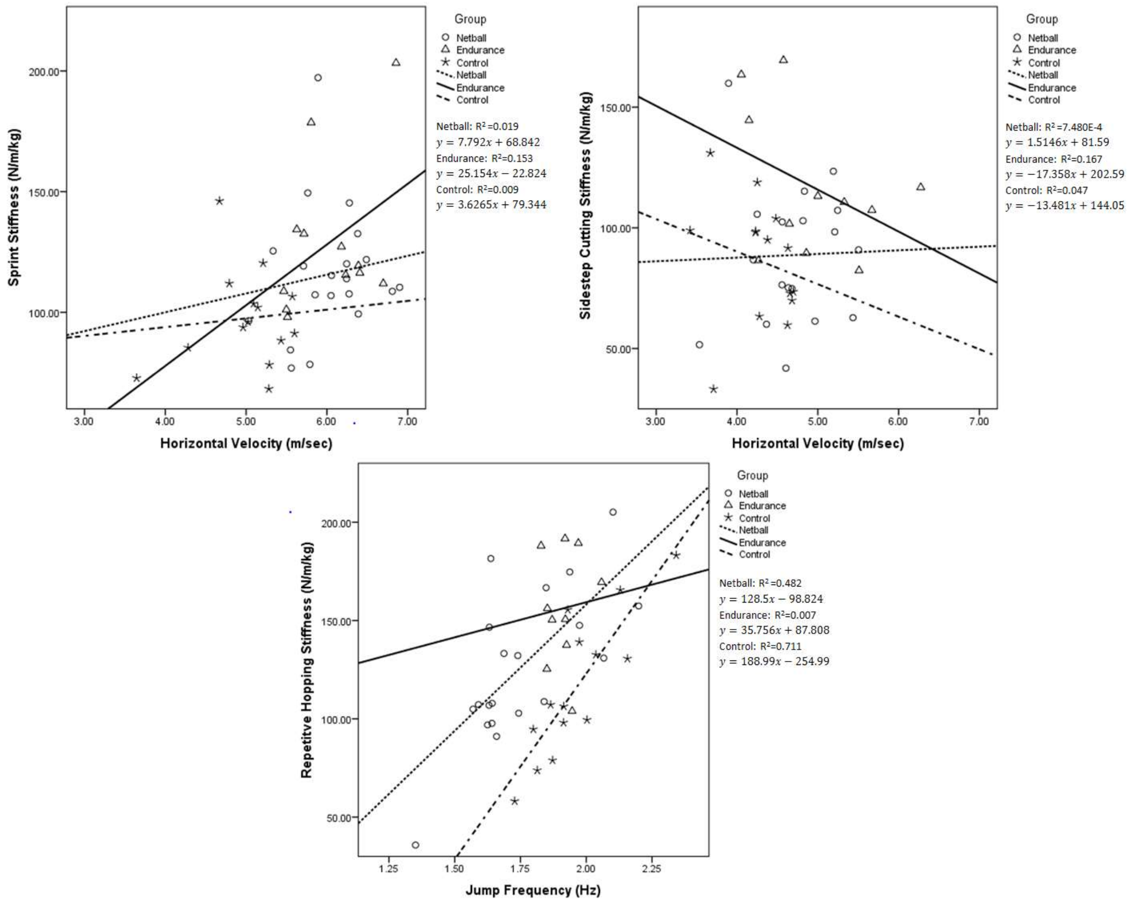

Figure 6.1- Linear regression stiffness and velocity/jump frequency plots of sprint, sidestep cutting and repetitive hopping tasks.

6.3.4.2 Performance Variables

To supplement stiffness measures, key performance variables which contribute to stiffness of the leg spring were assessed during the stiffness assessment tasks. These measures included peak vertical ground reaction force, contact time, centre of mass displacement, running velocity, jump frequency and jump height.

6.3.5 Statistical Analyses

Normality was evaluated utilising a critical appraisal approach (Peat & Barton, 2006). Outliers were removed from non-normal data with a maximum of three from any one group variable, prior to statistical analysis to ensure data was a valid representation of athletic population's stiffness profile. Outliers were defined as being greater than 1.5 x interquartile range as determined by Statistical Package for Social Sciences (SPSS, v21.0, Inc., Chicago, IL, USA) (Osborne & Overbay, 2004). One-way analysis of variance with Bonferroni post-hoc test were implemented to evaluate differences between each group in leg stiffness and contributory performance variables. Data which did not meet normal distribution or display homogeneity of variance were assessed using the equivalent non-parametric Kruskal-Wallis test.

Pearson correlations were implemented to assess the relationship of leg stiffness measures between each evaluated task (> 0.70 very strong, 0.50 - 0.69 strong, 0.30 - 0.49 moderate) (Peat & Barton, 2006). Variables that violated correlation assumptions were evaluated using Spearman correlations. Statistical analyses were undertaken using the Statistical Package for Social Sciences with an alpha level set at $p \leq 0.05$. Variables displaying p values with the range of 0.05 - 0.09 and an effect size greater than 0.50 were defined as providing a clinically meaningful difference (Cohen, 1988; Hopkins, 2005).

6.4 Results

Significant differences were evident in leg stiffness measures between groups for all assessed tasks (Table 6.2). Several differences were also evident in the variables which contribute to the stiffness of the leg spring between the three groups.

The results from the sprint test displayed significant differences in leg stiffness between control and endurance groups ($p = 0.017$). When assessing the contributing performance outcome variables for sprinting, significant differences were evident in the stiffness control mechanisms where both netball and endurance athletes displayed higher peak vertical ground reaction force ($p = 0.001$ - 0.011) and lower contact time ($p < 0.000$ - 0.003) when compared to the control group. Horizontal velocity was different between groups, with both netball ($p < 0.001$) and endurance ($p < 0.001$) athletes approaching contact significantly faster than the control group.

The analysis of the anticipated sidestep cutting task revealed endurance athletes were significantly stiffer than both control ($p = 0.002$) and netball groups ($p = 0.008$). Differences in peak vertical ground reaction force ($p = 0.001$) and centre of mass displacement ($p = 0.014$) were observed between groups. Peak vertical ground reaction force ($p = 0.057$) and contact time ($p = 0.069$) also displayed a clinically meaningful difference between netball and endurance athletes. Further, centre of mass displacement between control and netball groups ($p = 0.086$) and contact time amongst control and endurance groups ($p = 0.086$) revealed clinically meaningful differences. Both athletic groups approached contact with a significantly faster horizontal velocity than the control group ($p = 0.033 - 0.037$).

The evaluation of the repetitive hopping task revealed both athletic groups were significantly stiffer than the control group ($p < 0.001$). Inspection of the contributing variables utilized to optimize stiffness revealed differences in peak vertical ground reaction force ($p = 0.006 - 0.008$), centre of mass displacement ($p = 0.004$) and contact time ($p = 0.002 - 0.010$). Outcome performance measures of jump frequency ($p = 0.005 - 0.022$) and jump height ($p < 0.000 -0.014$) were significantly different between groups. Netball athletes displayed a clinically meaningful higher jump height than endurance athletes ($p=0.098$).

Table 6.2- *Analysis of Variance Assessing Leg Stiffness, Performance Outcome Variables and the Contributing Kinetic Measures during Sprints, Anticipated Cutting and Repeat Hopping Tasks. Values are mean (SD).*

		Control (*n*=14)	Netball (*n*=20)	Endurance (*n*=13)	Control– Netball Effect Size	Control – Endurance Effect Size	Netball – Endurance Effect Size
Sprint	**Leg Stiffness ($N^{-1}·m^{-1}·kg^{-1}$)**	96.24 (14.83)[c]	109.05 (19.01)	120.98 (28.96)[a]	0.76	1.13	0.50
	PVGRF (%BW)	2.50 (0.22)[bc]	2.75 (0.28)[a]	2.87 (0.15)[a]	1.00	2.00	0.56
	COMd (m)	0.04 (0.01)	0.03 (0.01)	0.04 (0.01)	1.00	0.00	1.00
	Horizontal Velocity ($m^{-1}·s^{-1}$)	5.00 (0.53)[bc]	6.03 (0.47)[a]	6.03 (0.49)[a]	2.06	2.02	0.00
	Contact Time (s)	0.186 (0.013)[bc]	0.166 (0.016)[a]	0.158 (0.017)[a]	1.38	1.87	0.49
Sidestep Cutting	**Leg Stiffness ($N^{-1}·m^{-1}·kg^{-1}$)**	81.74 (25.10)[c]	88.70 (29.14)[c]	122.36 (27.33)[ab]	0.26	1.55	1.19
	PVGRF (%BW)	2.27 (0.28)[c]	2.43 (0.26)	2.66 (0.21)[b]	0.59	1.59	0.98
	COMd (m)	0.04 (0.01)	0.05 (0.02)[c]	0.04 (0.01)[b]	0.67	0.00	0.67
	Horizontal Velocity ($m^{-1}·s^{-1}$)[NP]	4.28 (0.41)[bc]	4.69 (0.53)[a]	4.94 (0.70)[a]	0.87	1.19	0.41
	Contact Time (s)	0.212 (0.014)	0.211 (0.032)	0.189 (0.022)	0.04	1.28	0.82

		Control (n=14)	Netball (n=20)	Endurance (n=13)	Control–Netball Effect Size	Control – Endurance Effect Size	Netball – Endurance Effect Size
Repetitive Hopping	**Leg Stiffness ($N^{-1}·m^{-1}·kg^{-1}$)**	96.08 (19.58)[bc]	139.88 (27.96)[a]	154.23 (29.05)[a]	1.84	2.39	0.50
	Jump Height (m)	0.049 (0.021)[bc]	0.117 (0.040)[a]	0.089 (0.031)[a]	2.23	1.54	0.79
	PVGRF (%BW)	2.58 (0.37)[bc]	3.06 (0.47)[a]	3.13 (0.36)[a]	1.14	1.51	0.17
	COMd (m)	0.14 (0.02)[b]	0.17 (0.03)[ac]	0.14 (0.01)[b]	1.20	0.00	1.50
	Jump Frequency (Hz) [NP]	1.96 (0.16)[b]	1.76 (0.21)[ac]	1.91 (0.07)[b]	1.08	0.44	1.07
	Contact Time (s) [NP]	0.340 (0.047)[c]	0.318 (0.034)[c]	0.282 (0.041)[ab]	0.54	1.32	0.96

[a] Significantly different to control group; [b] Significantly different to netball group; [c] Significantly different to endurance group; [NP] Non parametric Kruskal-Wallis test implemented; Peak vertical ground reaction force (PVGRF); Centre of mass displacement (COMd).

The examination of correlations within each group evaluating the stiffness relationship between tasks revealed differences in the association between tasks (Table 6.3). The stiffness results for the control group displayed no relationships with any of the assessed tasks. Netball athletes displayed a clinically meaningful, moderate stiffness relationship between the two sports-specific tasks (p = 0.070). Additionally, both sports-specific tasks and repetitive hopping exhibited a moderate relationship among netballers. Leg stiffness of endurance athletes during the sprint and repetitive hopping tasks appeared to be moderately related.

Table 6.3- *Leg Stiffness Relationship between Assessed Tasks.*

	Sprint			**Cut**		
	Control	**Netball**	**Endurance**	**Control**	**Netball**	**Endurance**
Cut	0.081	0.449	0.121			
Repetitive Hopping	-0.308	0.331	0.491^{NP}	0.281	0.353	-0.024

† Significant correlation (p<0.05); ^{NP} Non parametric Spearman's rho test implemented.

6.5 Discussion

The present study evaluated leg stiffness and performance variables in female athletic populations during dynamic and functional tasks relevant to training background. Additionally, the study investigated the stiffness relationship between dynamic jumping and sports-specific tasks. Leg stiffness and contributing performance variable differences were observed between groups across all the assessed tasks supporting the hypothesis that athletes from varied training backgrounds would display leg stiffness and control strategy differences.

It was anticipated that differences in leg stiffness during sprinting would be evident in athletes due to variance in training background and its resultant influence on stiffness control strategies including strength, co-ordination, co-contraction and the intrinsic properties of muscle fibres. In line with previous research, the results of this study indicated endurance athletes displayed a stiffer leg spring than the control group (Hobara, Kimura, et al., 2010). It is suggested that this reflects the training and competition demands of endurance athletes where they are required to maximize running economy. Higher stiffness via minimal joint flexion and reduced vertical oscillation of the centre of mass allows for more effective force application and subsequently increased running efficiency (Bushnell & Hunter, 2007). As expected both athletic groups exhibited higher running velocity than the control group which was achieved through shorter contact time and higher peak vertical ground reaction forces evident in both groups. Shorter contact time and effective force application leads to increased leg stiffness and subsequently performance enhancement demonstrated by both athletic groups through higher running velocity. Although results did not display significant differences in stiffness between netball athletes and the assessed groups, it would appear netballers utilize stiffness more effectively to achieve superior performance when compared to the control group evident through shorter ground contact time and higher running velocity (Arampatzis et al., 1999). However, the mechanistic joint control strategies populations utilize to meet performance demands of tasks requires further investigation.

Similar to the sprint results, endurance athletes exhibited a stiffer leg spring than netball and control groups during the anticipated sidestep cutting task. Although endurance athletes achieved a stiffer leg spring and netball athletes display stiffness similar to that of the control group, it would appear only netballers achieved adequate stiffness levels to meet task demands evident through the linear regression. Although individual stiffness modulation was not evaluated through linear regression, the slopes suggest netball athletes' more effectively utilize stiffness. Endurance and control groups, who are unaccustomed to this task displayed, reduced leg stiffness with increasing horizontal velocities suggesting an inability to adequately attenuate leg stiffness to meet the demands of the task. Endurance athletes displayed inherently higher leg stiffness, a result of a shorter contact time and minimal joint flexion, arguably a necessity for economically efficient movements. However, it is postulated that high leg stiffness may not be beneficial for performance during a cutting task. Thus, higher stiffness scores reflected in endurance athletes may not reflect better performance, rather they may represent an inherent training response to loading. While the leg stiffness levels of netball and control groups appear similar, unlike the control group, netball athletes appear to apply a similar stiffness strategy to meet the task demands. It is suggested this reflects netballers' neuromuscular training adaptations to high velocity rotational change of direction movements. Previous research has suggested higher stiffness is necessary for performance enhancement, however contrasting ideas indicate optimal levels of stiffness are dependent on the tasks and the associated performance demands (Butler et al., 2003; Komi, 2000). Furthermore, research has speculated that higher stiffness may be detrimental for high impact reactive tasks, where boundaries appear evident in the capacity for stiffer subjects to attenuate high eccentric loads (Walshe & Wilson, 1997). It can be proposed that this may be the case for the sidestep cutting task were athletes accustomed to the task, such as netballers, display lower levels of stiffness to meet task demands, achieved through greater centre of mass displacement to allow for a land and sidestep pushing motion. Further research is required to assess the kinematic and kinetic strategies that athletes utilize to meet the demands of the task. Comparable to the sprint task both athletic groups approached the task with higher running velocity and greater peak vertical ground reaction force than the control groups, necessary for optimal performance.

In congruence with previous research assessing repetitive hopping, the athletic groups displayed higher stiffness than the control group and subsequently accomplished superior jump heights in the current study (Hobara, Kimura, et al., 2010). The results revealed the control group were unable to modulate stiffness effectively in order to meet the demands of the task, as indicated through longer contact time, lower peak vertical ground reaction force and subsequently lower hop heights. As discussed, sport specific training influences the neuromuscular stiffness control strategies and subsequently the kinematic and kinetic movement patterns of athletes. Similar to the sprint and sidestep cutting task, endurance athletes displayed shorter contact times reflective of their training requirements where athletes need to utilize economically efficient movement patterns in order to optimize elastic energy storage and return to meet task demands. Furthermore, athletic groups displayed greater force application during hopping aiding in their ability to optimize stiffness to achieve the performance demands of the task. Identical to the sidestep cutting task, during the repeat jumps netball athletes displayed greater displacement of the centre mass and exhibited the best jump performance, suggesting due to their training and competition demands netball athletes are able to effectively optimize stiffness to meet the demands of the task.

The relationship of stiffness between tasks further reflected the notion that athletic training inherently influences the stiffness optimization of athletes to meet task demands. It was hypothesized that stiffness during dynamic reactive jumping tasks would be related to stiffness values during sports-specific tests. The results of the present study generally did not support this hypothesis, however some interesting relationships between tasks were observed which appear to support the influence of training on leg stiffness. The control group displayed no relationships for stiffness between all of the assessed tasks. It is suggested that these findings may be attributed to the lack of any specific athletic training or exposure to repeat effort tasks or rotational movements. Subsequently, untrained participants do not appear to utilize any common strategy to optimize leg stiffness to meet tasks demands. In contrast, training of netballers requires athletes to perform maximal jumping efforts, repeated sprints and cutting manoeuvres. Thus it is theorized that the stiffness between tasks among netballers may be related due to neuromuscular adaptations to all tasks. The results of this study supported this hypothesis along with previous research where stiffness of netball athletes appeared to exhibit moderate relationship between sports-specific tasks (Millett et al., 2013). Further, the correlation results of endurance athletes reinforced the concept that stiffness optimization is task dependant. Endurance athletes displayed a moderate relationship for the stiffness results from sprinting and repetitive hopping. Although repetitive hopping does not specifically reflect the movements of endurance athletes, this activity is utilized in the daily training environment as a plyometric exercise to develop strength and economy efficiency and is the most closely related activity to their training requirements (Spurrs, Murphy, & Watsford, 2003). Additionally, endurance athletes displayed no relationship between the sidestep cutting task and either assessed task representative of movement during their daily training environment. This appears to further emphasize the notion that stiffness optimization is dependent on an athlete's training background. Future investigation of the kinematic and kinetic stiffness control strategies that groups utilize to meet task demands may provide further insight into leg stiffness relationships and training background across various tasks.

Previous research has suggested basic jumping tasks are unrelated to sports-specific tests and lack the necessary sensitive to distinguish stiffness differences between athletic groups (Millett et al., 2013; Millett et al., 2015, 2016). This indicates sports-specific and dynamic tasks may be preferable in the assessment of leg stiffness in athletes (Millett et al., 2013; Millett et al., 2015). The present study is one of few studies to assess female participants from varying training backgrounds during sports-specific functional tests. The results established key stiffness differences between groups, indicating that training associated variations in stiffness exist between tasks. These differences highlight the importance of utilizing dynamic sport specific functional tests in athlete screening and monitoring. Efficient athlete screening and monitoring tools are key for enhanced performance and injury risk minimization. The results of this study provide evidence suggesting repetitive hopping may be used as a daily monitoring tool for stiffness assessment in athletic populations due to its moderate relationship to relevant sport specific tasks. However, it is important to note that the use of sports-specific tests serve as gold standard assessments for practitioners screening for lower limb stiffness differences.

6.6 Practical Applications

The results of this study established differences in leg stiffness between female sub-populations during sports-specific and dynamic jumping tasks. It appears that between group differences in leg stiffness exist due to inherent training variance, subsequently influencing the control strategies that populations utilize. Furthermore, the training background of athletes appears to influence the stiffness relationship between tasks. The results provide practical evidence suggesting that sport-related dynamic tasks should be utilized to assess stiffness within athletic populations. Although sports-specific tasks serve as a direct reflection of stiffness during training and competition, these tasks are potentially impractical monitoring tools for athletes, coaches and practitioners as they typically require the use of motion analysis and are limited to a laboratory setting. The moderate relationship observed between the repetitive hopping task and sports-specific tasks in athletic groups suggests this test may provide a suitable 'intermediate' monitoring tool to assess an athlete's stiffness during daily training. Accordingly, practitioners monitoring lower limb stiffness and evaluating differences from a performance capacity or injury risk identification perspective should consider utilizing appropriate dynamic tests relevant to athletic populations.

6.7 Acknowledgments

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6.8 Summary and Key Findings

Chapter 6 established clear differences in leg stiffness between athletic populations. It may be postulated that this occurs due to inherent variations in training and conditioning. It was also apparent that an athlete's training background influenced the observed stiffness relationships between tasks. In athlete screening and monitoring, it appears sports-specific tasks are the most appropriate tools for the assessment of lower-extremity stiffness for performance and injury risk monitoring as they provide a typical reflection of an athlete's stiffness properties during training and competition. Although advantageous, due to the limitation of sport-specific tasks to a laboratory setting, it is suggested that repetitive hopping may serve as a simpler intermediate monitoring tool.

6.9 Recommendations for Future Research

A need exists to explore the underlying mechanisms athletes utilise at the joint level to modulate stiffness in order to meet sports-specific performance demands. Although chronic athletic training influences leg stiffness, it still remains unclear as to how athletic training influences stiffness contributions at the joint level. Assessment of joint stiffness and contributory mechanisms may provide insight into why only a moderate relationship is observed between sports-specific tasks and the dynamic repetitive hopping task.

6.10 Importance of Chapter 7

As highlighted by the results of Chapter 6, a need exists to assess the underlying mechanisms which contribute to the modulation of leg stiffness during sports-specific and dynamic tasks as few studies have investigated the contributory mechanisms during tasks relevant to an athlete's training background. Enhanced understanding of the mechanisms which contribute to lower-extremity stiffness during sports-specific tasks may provide further knowledge of how athletes meet performance demands and contribute to an increased understanding of the mechanisms which may contribute to injury risk.

Chapter 7 evaluated Aim 3 of the thesis:

Aim 3 – To evaluate differences in leg and joint stiffness in varying female athletic sub-populations and subsequent kinematic and kinetic mechanisms athletic populations utilise to modulate stiffness to meet sports-specific task demands.

Chapter 7. Study 3: Variations in Lower Body Stiffness Modulation Strategies During Sports-Specific Tasks in Well Trained Female Athletes

7.1 Abstract

This study aimed to evaluate differences in leg stiffness, joint stiffness and the contributory kinematic and kinetic stiffness modulation strategies athletes from varying training backgrounds utilise during sport specific activities and dynamic hopping tasks. Forty-seven female participants (20 nationally identified netballers, 13 high level endurance athletes and 14 age and gender matched controls) completed sprint, anticipated change of direction and unilateral repetitive hopping tasks. Data was captured with a 10 camera motion analysis system and force plate and compared between training backgrounds. Significant differences were observed in leg stiffness, joint stiffness and the contributory joint control strategies between groups across all investigated tasks ($p<0.001$-0.043). Results also indicated that athletic populations display clear modulation strategies that reflect their training background, while the control group displayed no clear modulation strategy. Understanding the differences in the kinematic and kinetic stiffness modulation strategies athletes utilise to meet the demands training and competition can provide insight into the influence of chronic athletic training on leg and joint stiffness and its subsequent effect on performance and injury risk.

KEYWORDS Leg stiffness; joint stiffness; athletic training; sprinting; change of direction; hopping; females

7.2 Introduction

Lower limb mechanics which contribute to performance have been described as the ability of the system properties to resist the applied stretch of an external load (Butler et al., 2003). This phenomenon is known as lower-extremity stiffness (Brughelli & Cronin, 2008a, 2008b). Lower-extremity stiffness can be portrayed through the spring mass model, whereby a single linear spring is compressed during ground contact, subsequently controlling the lowering of the centre of mass and allowing for the storage and return of elastic energy (Brughelli & Cronin, 2008b). Stiffness calculations have also been extended to modelling stiffness of a single joint (hip, knee or ankle) as a rotational spring to provide insight into joint contributions to stiffness of the leg spring (Butler et al., 2003).

The optimisation of leg and joint stiffness is essential to facilitate athletic performance and minimise the risk of injury incidence, however stiffness optimisation is dependent upon the force production, absorption and rate at which force is produced characteristics (Butler et al., 2003). Research has established links between stiffness to both performance and injury risk (Ambegaonkar et al., 2011; Comyns et al., 2007; Hobara, Inoue, et al., 2010; Hobara, Kimura, et al., 2010; Laffaye et al., 2005; Toumi et al., 2004; Watsford et al., 2010). Higher levels of stiffness have been associated with an elevated risk of overuse, bone related injuries (Butler et al., 2003; Hobara, Kimura, et al., 2010). Further, lower levels of stiffness appear to be linked to soft tissue injury risk and may contribute to excessive joint motion (Butler et al., 2003). By enhancing the stiffness of the leg spring and joint, higher levels of elastic energy and rapid transmission of impact forces are able to occur, allowing athletes to maximise performance capacity. Few studies have investigated the leg and joint stiffness contributions during tasks relevant to athletic training and competition. Of the studies which have investigated this concept they suggest that a stiffer knee and ankle joint may be advantageous in achieving a shorter ground contact and enhanced mechanical efficiency during sprint locomotion (Arampatzis et al., 1999; Kuitunen, Komi, et al., 2002).

Joint stiffness is dependent on a multitude of factors including muscle activation, joint angle, range of motion and angular velocity of the joint during ground contact (Brughelli & Cronin, 2008b; Butler et al., 2003; Kuitunen, Komi, et al., 2002). Stiffness of a single joint describes the ratio of change in joint moment to angular displacement of the individual joint, acting as a stabiliser for the leg spring (Kuitunen, Komi, et al., 2002; Stefanyshyn & Nigg, 1998). The stiffness of the joint also contributes to the work of the muscle through optimisation of the stretch shortening cycle which allows for increased velocity of the centre of mass. Interestingly, there has been limited research investigating the contribution of joint stiffness in the modulation of lower-extremity stiffness. Ankle stiffness appears to play a key role in modulating stiffness of the leg spring during hopping (Farley & Morgenroth, 1999; Hobara, Kimura, et al., 2010), whereas knee joint stiffness acts as the main contributor during running (Arampatzis et al., 1999; Kuitunen, Komi, et al., 2002). However, the mechanical control and joint contribution to stiffness modulation is relatively unknown amongst athletic groups, particularly during sport specific tests which incorporate the coordination of multiple joints.

Stiffness control of the leg spring and individual joint is dependent upon the co-contraction of agonist and antagonist muscles, muscle pre-activation and neuromuscular regulation (Butler et al., 2003). Stiffness adjustment is also reliant upon the task demands, the individual's training status and the athletic background of individuals (Komi, 2000). Athletic training and conditioning aids the development of key kinematic and kinetic stiffness modulation strategies athletes utilised to meet performance demands (Ambegaonkar et al., 2011; Bushnell & Hunter, 2007; Kuitunen, Komi, et al., 2002; Kuitunen et al., 2007; Kuitunen et al., 2011). For example, research has established that endurance runners need to maximise efficiency by minimising flexion of the joints and vertical oscillation of the centre of mass during repetitive hopping (Hobara, Kimura, et al., 2010).

In elite sport, early identification of injury risk is essential to provide the opportunity for relevant implementation of preventative strategies. Recent research has suggested that functional and sports-specific tests may be superior screening tools when compared to discrete maximal jump tasks traditionally implemented to assess stiffness and its contributory mechanisms (Millett et al., 2015). In order to gain an insight into the mechanisms that contribute to injury risk, it is important to understand the kinematic and kinetic modulation strategies athletic populations utilise to meet task demands. However, the influence of training background on leg and joint stiffness modulation strategies in athletic populations during functional and sports-specific tests remains unclear, particularly amongst females.

Therefore, the purpose of this study was; 1) to examine the differences in leg stiffness and joint stiffness in female athletes from different training backgrounds during functional tasks, and 2) to investigate the kinematic and kinetic mechanisms that sub-populations utilise to modulate stiffness during sport specific task demands. It was hypothesised that leg stiffness, joint stiffness and the underlying mechanisms which contribute to stiffness modulation would vary between the investigated sub-populations during dynamic reactive jump tasks and sports-specific tests as a result of their varied training and conditioning backgrounds.

7.3 Methods

7.3.1 Experimental Approach to the Problem

This cross sectional study assessed two sub populations from different athletic training backgrounds, along with non-active control participants. The focus of this study was to assess the stiffness of the leg spring in the participant's dominant leg, joint stiffness and the underlying joint mechanisms which contribute to stiffness modulation populations utilise to regulate stiffness during three sports-specific functional movements.

7.3.2 Subjects

Forty-seven female participants (20 nationally identified netballers, 13 high level endurance athletes and 14 age and gender matched controls) volunteered to participate in this study (Table 7.1). Written informed consent, or where applicable, parental consent, was provided by all participants. Participants were injury free at time of testing, defined as not missing or modifying two consecutive training/competition sessions within two weeks prior to testing (Kirialanis et al., 2003). All testing procedures were approved by the Human Research Ethics Committee of the Australian Catholic University. The populations recruited for this study were targeted due to their different training and competition demands and their reliance on activities involving the stretch-shortening cycle. Netball athletes were representative of a high intensity, intermittent sport requiring maximal jumping efforts, explosive sprints and change of direction movements. Endurance athletes (1500m – marathon) were representative of a group where the training demands require athletes to perform continuous, efficient locomotion at submaximal intensity. Control group participants did not exceed four hours of weekly physical activity (Loud et al., 2005).

Table 7.1- *Participant Descriptive Information. Values are Mean (SD).*

Group	N	Age (Years)	Mass (kg)	Height (cm)	Weekly Training Hours ($h.wk^{-1}$)	Training Years
Netball	20	17.4 (1.5)	69.2 (8.4)	178.1 (5.6)	7.9 (4.8)	6.4 (3.6)
Endurance	13	19.7 (4.0)	53.4 (2.9)	165.9 (4.8)	10.0 (3.4)	7.5 (2.5)
Control	14	22.1 (2.3)	59.6 (9.9)	162.9 (5.5)	2.1 (1.2)	-

7.3.3 Testing Procedures

Data collection took place immediately prior to the commencement of each athletic population's competition season. Participants performed a self-directed, whole body dynamic warm up consisting of a combination of approximately 5-10 minutes of jogging or cycling on an exercise bike followed by 10 minutes of simple dynamic, lower body mobility drills (e.g. high knees, landing and agility drills), prior to completing five trials of three functional and sports-specific tasks; these included sprint, anticipated sidestep cutting and repetitive hopping. These tasks have been identified within the literature as appropriate screening tools and display adequate sensitivity to identify differences between these identified athletic populations (Millett et al., 2015). Participants performed familiarisation trials following a demonstration until they were comfortable with the task and displayed a continuous coordinated movement. To ensure order effects did not bias data, task order was randomised, with the exception of the repetitive hopping task which was performed last to ensure fatigue did not influence results. All tasks were performed on the participant's dominant leg. Leg dominance was defined using a modified protocol based on the methods of Padua et al. (2006).

7.3.3.1 Sprint

A 40 metre sprint was performed by participants at their event competition pace. Force measures and kinematic variables necessary for leg stiffness calculations were collected at 30 m. To ensure trials reflected movement patterns of athletes in the daily training environment participants were discouraged from decelerating or overextending to strike the force plate.

7.3.3.2 Anticipated Sidestep Cutting

An anticipated cutting task was included to represent the sharp change of direction cutting movements commonly performed by high intensity intermittent sporting populations. Participants approached the cut with a speed representative of competition pace, landed on the force platform and pushed diagonally sideways to re-accelerate. A target angle of between 30-40 degrees relative to the direction of the contact point of the dominant leg (McLean et al., 2004) was marked on the floor and the non-dominant foot contact immediately following the change of direction was required to fall within this angle range for a valid trial.

7.3.3.3 Repetitive Hopping

Repetitive hopping may serve as a simplistic task where stiffness measures reflect stiffness generated during sports-specific movements (Millett et al., 2015). Participants were asked to perform 27 continuous, reactive hops at a self-selected submaximal intensity. The first five and last two trials were excluded from analysis with the mean of the remaining 20 trials included in subsequent evaluation (Moresi et al., 2014). Target vertical eye heights, ascertained from familiarisation trials, were set at 70% of maximal jump height representative of submaximal intensity to ensure the repeatability and reliability of the hops. Participants were asked to perform the task on their dominant leg and advised to keep their hands positioned on their hips to minimise the contribution of arm swing to jump height (Harman et al., 1990; Luhtanen & Komi, 1979).

7.3.3.4 Data Collection

Kinematic data was captured with a ten camera motion analysis system sampling at 500 Hz (Vicon MX; Oxford, United Kingdom). Ground mounted force plates covered with a Mondo track surface sampling at 1000 Hz were utilised to acquire kinetic data (Advanced Mechanical Technology Inc., Watertown, U.S.A. and Kistler, 9281CA, Switzerland). Standardised anthropometric measures were implemented in the standard Vicon Plug-in-gait full body model (Vicon; Oxford, United Kingdom) and utilised to determine centre of mass displacement (COMd).

7.3.4 Data Analyses

Following analysis of the frequency content and residuals of the power spectra in kinematic data (Winter, 2005) a cut off frequency of 23 Hz for sprint and sidestep cutting, and 16 Hz for repetitive hopping, was implemented in a dual, low pass, fourth order Butterworth filter. Leg and joint stiffness measures were isolated to the eccentric phase of movement where elastic energy storage occurs.

7.3.4.1 Leg and Joint Stiffness

Leg stiffness was calculated as the peak vertical ground reaction force (PVGRF) divided by the change in leg length. Change in length accounted for the initial leg length of the individual, vertical displacement of the centre of mass, horizontal velocity at impact and contact time (CT) (McMahon & Cheng, 1990). To provide a typical representation of the individual's leg spring during running based tasks, the highest and lowest stiffness scores of the five trials were eliminated with the mean of each participant's middle three scores implemented in subsequent analysis (Stalbom et al., 2007). Residual calculations derived from population specific linear regression analysis were implemented to standardise leg stiffness measures to the average horizontal touchdown velocity or jump frequency of all participants. Scores were also normalised to body weight. Joint stiffness of the hip, knee and ankle were determined as the ratio of change in joint moment to angular displacement of the joint (Farley et al., 1998).

7.3.4.2 Contributing Kinematic Mechanisms to Stiffness Modulation

To supplement stiffness measures, key contributory kinematic and kinetic mechanism strategies female sub-populations utilise to modulate stiffness of the leg spring to meet task demands were assessed. These measures included joint displacement, joint moment and touchdown angles of the hip, knee and ankle.

7.3.5 Statistical Analyses

Normality was evaluated utilising a critical appraisal approach (Peat & Barton, 2006). Outliers were removed from non-normal data with a maximum of three from any one group variable, prior to statistical analysis to ensure data was a valid representation of the population's stiffness profile. Outliers were defined as being greater than 1.5 x interquartile range (Osborne & Overbay, 2004). One-way analysis of variance with Bonferroni post-hoc test were implemented to evaluate differences in leg stiffness, joint stiffness and contributory mechanisms which modulate stiffness between each group. Data which violated normal distribution criterion or homogeneity of variance was evaluated using the equivalent non-parametric Kruskal-Wallis test.

Pearson correlations were implemented to evaluate the relationship of isolated joint stiffness and the associated kinematic contribution to the overall leg stiffness score of each group (>0.7 very strong, 0.5-0.69 strong, 0.3-0.49 moderate) (Peat & Barton, 2006). Spearman rank-order correlations where implemented to assess non-normally distributed variables. Statistical analyses were undertaken using the Statistical Package for Social Sciences (SPSS, v21.0, Inc., Chicago, IL, USA) with an alpha level set at $p<0.05$. Given the number of statistical analysis Bonferroni correction was considered to reduce the chance of type 1 error, however research has deemed this process to be too stringent in an applied sports research study (Bland & Altman, 1995; Perneger, 1998). Effect sizes were also calculated to assess differences between groups (Cohen, 1988). Variables displaying p values with the range of 0.05-0.09 and an effect size greater than 0.50 were defined as providing a clinically meaningful difference (Hopkins, 2005).

In order to provide further insight into the inferential statistical analysis evaluating the joint stiffness contributions to leg stiffness, a principal component analysis (PCA) was conducted. PCA is a multivariate statistical technique used to investigate the maximal amount of inter-subject variance throughout a data set to objectively observe differences between subject groups during the evaluated tasks. PCA consists of an orthogonal transformation of potentially correlated variables and coverts the variables into uncorrelated principal components, reducing the dimensionality of the data. A weighted PCA was performed on leg, hip, knee and ankle stiffness scores using the inverse variance of the variables as weighted co-efficients. The resultant weighted coefficient matrix was transformed to correct for the data being not orthonormal. A bi-plot was created to visually assess the organisation of participant scores and orthonormal coefficients to the first two principal components. All PCA calculations were performed using MATLAB 2014a (Mathworks, Natick, MA).

7.4 Results

There were differences evident in leg and joint stiffness measures between groups in all evaluated tasks. Further, differences were also evident between the three groups in the contributory mechanisms associated with stiffness modulation.

The sprint task revealed endurance athletes displayed a stiffer leg spring than the control group ($p=0.017$) (Table 7.2). At the joint level, the netball athletes displayed a stiffer knee ($p=0.003$-0.008) and ankle joint ($p=0.016$-0.024) than both control and endurance groups. Inspection of the kinematic mechanisms utilised by netball athletes to modulate compression of the leg spring revealed differences in hip touchdown angle ($p=0.035$), knee angular displacement ($p=0.004$-0.005), knee touchdown angle ($p=0.001$-0.007) and ankle peak moment ($p<0.001$). Endurance athletes tended to display less hip flexion than netball athletes (p=0.068) and the control group tended to approach contact with less flexion than endurance athletes (p=0.080). Further, the control group displayed a clinically meaningful difference in ankle touchdown angle (p=0.067) when compared to netball athletes and was significantly different to the endurance group (p=0.042).

Examination of correlations within each group revealed differences in contributions from joint stiffness and the associated contributory mechanisms to leg stiffness during sprinting (Table 7.2). Stiffness in the control group displayed a strong to moderate relationship to ankle angular displacement (r=-0.496; p=0.085) and a moderate relationship was also observed between leg stiffness and ankle stiffness (r=0.346; p=0.270) and knee peak moment (r=0.462; p=0.112). In contrast there was a negative relationship between stiffness and knee peak moment (r=-0.401; p=0.099) in netballers, along with a moderate relationship to knee touchdown angle (r=-0.375; p=0.125), ankle stiffness (r=0.366; p=0.135) and ankle peak moment (r=0.376; p=0.124). While stiffness for endurance athletes exhibited a moderate relationship with knee touchdown angle (r=-0.461; p=0.132), ankle stiffness (r=-0.302; p=0.339) and ankle touchdown angle (r=-0.357; p=0.254).

Table 7.2- *Stiffness Control Mechanisms and their Relationship with Leg Stiffness during the Sprint Assessment. Values are mean (SD).*

Sprint	Control (*n*=14)	Control Relationship to Kleg (r)	Netball (*n*=20)	Netball Relationship to Kleg (r)	Endurance (*n*=13)	Endurance Relationship to Kleg (r)
Leg Stiffness ($N^{-1}\cdot m^{-1}\cdot kg^{-1}$)	96.24 (14.83)[c]		109.05 (19.01)		120.98 (28.96)[a]	
Horizontal Velocity ($m^{-1}\cdot s^{-1}$)	5.00 (0.53)[bc]		6.03 (0.47)[a]		6.03 (0.49)[a]	
Hip Stiffness ($N\cdot m^{-1}\cdot deg^{-1}\cdot kg^{-1}$)*	0.043 (0.138)	-0.033	0.064 (0.183)	0.070	0.223 (0.294)	-0.164
Hip Peak Joint Moment ($N\cdot m^{-1}\cdot kg^{-1}$)	2.25 (1.63)	-0.168	3.23 (1.81)	0.096	3.76 (2.13)	-0.170
Hip Angular Displacement (deg)	13.09 (2.55)	-0.301	13.31 (2.83)	-0.292	10.75 (3.34)	-0.151
Hip Touchdown Angle (deg)*	37.56 (12.14)[b]	-0.224	46.66 (8.43)[a]	0.022	45.34 (5.74)	0.137
Knee Stiffness ($N\cdot m^{-1}\cdot deg^{-1}\cdot kg^{-1}$)*	0.182 (0.054)[b]	0.230	0.316 (0.142)[ac]	-0.258	0.197 (0.060)[b]	-0.087
Knee Peak Joint Moment ($N\cdot m^{-1}\cdot kg^{-1}$)	2.48 (0.73)	0.462	2.60 (0.75)	-0.401	2.78 (1.32)	-0.053
Knee Angular Displacement (deg)	20.86 (4.25)[b]	-0.243	15.13 (5.29)[ac]	-0.011	21.03 (4.42)[b]	-0.123
Knee Touchdown Angle (deg)	23.08 (7.68)[b]	0.197	33.68 (7.71)[ac]	-0.375	24.65 (6.91)[b]	-0.461
Ankle Stiffness ($N\cdot m^{-1}\cdot deg^{-1}\cdot kg^{-1}$)	0.115 (0.036)[b]	0.346	0.158 (0.046)[ac]	0.366	0.112 (0.046)[b]	-0.302
Ankle Peak Joint Moment ($N\cdot m^{-1}\cdot kg^{-1}$)*	2.37 (0.37)[b]	0.045	3.10 (0.55)[a]	0.376	2.60 (1.05)	0.257
Ankle Angular Displacement (deg)	20.74 (4.15)	-0.496	21.56 (6.24)	-0.066	24.54 (6.80)	0.106
Ankle Touchdown Angle (deg)	8.93 (7.19)[c]	-0.079	0.90 (9.86)	-0.263	-0.71 (10.69)[a]	-0.357

[a] Significantly different to control group; [b] Significantly different to netball group; [c] Significantly different to endurance group; * Non parametric Kruskal-Wallis test implemented; – negative ankle touchdown angles indicates plantar-flexion.

Results of the anticipated sidestep cutting task indicated the endurance group were stiffer than both the netball (p = 0.008) and control groups (p=0.002) (Table 7.3). Evaluation of joint stiffness revealed that endurance athletes displayed a significantly stiffer hip than netball athletes (p=0.040) and a clinically meaningful stiffer hip than the control group (p=0.090). Further, at the knee, netball athletes were stiffer in comparison to control and endurance groups (p=0.006-0.028, respectively). Significant differences were observed between groups in the contributory mechanisms of hip peak moment (p=0.006-0.032), hip angular displacement (p=0.005), knee peak joint moment (p<0.001-0.009), knee touchdown angle (p≤0.001), ankle peak joint moment (p<0.001-0.043) and ankle touchdown angle (p=0.006-0.029). Clinically meaningful differences in hip (p=0.055) and ankle (p=0.061) angular displacement between netball and control groups were evident.

Similar to the sprint results, the anticipated sidestep cutting task displayed differences in the mechanistic contributions utilised by each group to modulate stiffness (Table 7.3). A strong relationship was evident between leg stiffness and hip angular displacement (r=-0.515; p=0.059), knee stiffness (r=0.534; p=0.049) and ankle peak moment (r=0.611; p=0.020) in the control population. The control group also displayed a moderate relationship in knee angular displacement (r=-0.376; p=0.185), ankle stiffness (r=0.336; p=0.240) and ankle touchdown angle (r=-0.451; p=0.106). Leg stiffness of netball athletes displayed a very strong negative relationship to knee angular displacement (r=-0.784; p<0.000), and a strong relationship between knee stiffness (r=0.581; p=0.018), ankle stiffness (r=0.490; p=0.046) and ankle peak moment (r=0.670; p=0.003). Similarly, a moderate negative relationship between leg stiffness and hip (r=-0.406; p=0.215) and knee angular displacement (r=-0.425; p=0.192) was evident for the endurance group.

Table 7.3- *Stiffness Control Mechanisms and their Relationship with Leg Stiffness during the Change of Direction Cutting Assessment. Values are mean (SD).*

Anticipated Sidestep Cutting	Control (*n*=14)	Control Relationship to Kleg (r)	Netball (*n*=20)	Netball Relationship to Kleg (r)	Endurance (*n*=13)	Endurance Relationship to Kleg (r)
Leg Stiffness ($N^{-1}\cdot m^{-1}\cdot kg^{-1}$)	81.74 (25.10)[c]		88.70 (29.14)[c]		122.36 (27.33)[ab]	
Horizontal Velocity ($m^{-1}\cdot s^{-1}$)*	4.28 (0.41)[bc]		4.69 (0.53)[a]		4.94 (0.70)[a]	
Hip Stiffness ($N\cdot m^{-1}\cdot deg^{-1}\cdot kg^{-1}$)*	0.168 (0.147)	-0.194	0.138 (0.197)[c]	-0.210	0.467 (0.541)[b]	-0.200
Hip Peak Joint Moment ($N\cdot m^{-1}\cdot kg^{-1}$)*	3.29 (1.38)[bc]	-0.099	5.18 (2.36)[a]	0.017	6.51 (3.17)[a]	-0.092
Hip Angular Displacement (deg)	10.68 (3.47)	-0.515	13.80 (3.90)[c]	0.076	9.16 (3.06)[b]	-0.406
Hip Touchdown Angle (deg)	34.92 (12.21)	-0.013	44.83 (9.89)	-0.156	44.37 (7.38)	0.002
Knee Stiffness ($N\cdot m^{-1}\cdot deg^{-1}\cdot kg^{-1}$)	0.107 (0.026)[b]	0.534[d]	0.177 (0.050)[ac]	0.581[d]	0.115 (0.090)[b]	-0.002
Knee Peak Joint Moment ($N\cdot m^{-1}\cdot kg^{-1}$)*	2.43 (0.60)[b]	0.145	3.57 (0.68)[ac]	-0.191	1.89 (2.17)[b]	-0.064
Knee Angular Displacement (deg)	29.47 (5.53)	-0.376	29.11 (7.28)	-0.784[d]	29.14 (4.87)	-0.425
Knee Touchdown Angle (deg)	15.82 (6.34)[b]	0.070	27.44 (4.93)[ac]	-0.021	19.19 (5.99)[b]	-0.087
Ankle Stiffness ($N\cdot m^{-1}\cdot deg^{-1}\cdot kg^{-1}$)*	0.085 (0.024)	0.336	0.094 (0.026)	0.490[d]	0.098 (0.025)	-0.303
Ankle Peak Joint Moment ($N\cdot m^{-1}\cdot kg^{-1}$)*	2.08 (0.45)[bc]	0.611[d]	2.81 (0.37)[a]	0.670[d]	2.99 (1.49)[a]	-0.082
Ankle Angular Displacement (deg)	25.78 (7.17)	-0.240	31.97 (7.2)	-0.197	27.92 (7.11)	-0.036
Ankle Touchdown Angle (deg)*	3.61 (12.17)[bc]	-0.451	-7.68 (10.64)[a]	0.036	-7.35 (13.91)[a]	-0.066

[a] Significantly different to control group; [b] Significantly different to netball group; [c] Significantly different to endurance group; [d] Significant correlation ($p<0.05$); * Non parametric Kruskal-Wallis test implemented; – negative ankle touchdown angles indicates plantar-flexion.

Evaluation of the repetitive jump task established that both athletic groups displayed a significantly stiffer leg spring than the control group ($p<0.001$) (Table 7.4). Endurance athletes were significantly stiffer at the ankle when compared to the control group ($p=0.004$). Differences in the contributory mechanisms of hip touchdown angle ($p=0.004$), knee peak joint moment ($p=0.002$-0.006), ankle peak joint moment ($p=0.004$-0.027) and ankle touchdown angle ($p=0.014$) were apparent between the observed groups. Analysis of knee angular displacement revealed clinically meaningful differences between netball athletes and both investigated groups ($p=0.066$-0.083), with netball athletes displaying larger ranges of flexion at the knee. Clinically meaningful differences were also observed in hip touchdown angle between control and netball groups ($p=0.096$), with netball athletes approaching contact with a higher flexion angle at the hip.

The results of the repetitive hopping task indicated that ankle stiffness was a key contributor to leg stiffness across all groups ($r=0.449$-0.798; $p=0.006$-0.065) (Table 7.4). Further, the stiffness in the control population displayed a very strong relationship to ankle peak moment ($r=0.759$; $p=0.002$) and a moderate relationship to hip stiffness ($r=-0.350$; $p=0.241$). In contrast, netball athletes displayed a very strong relationship to ankle peak moment ($r=0.793$; $p<0.000$) and a strong relationship to knee stiffness ($r=0.519$; $p=0.019$). Moderate relationships were also observed with hip ($r=-0.455$; $p=0.050$) and knee angular displacement ($r=-0.407$; $p=0.075$), knee peak moment ($r=0.357$; $p=0.123$) and leg stiffness. In congruence with netball athletes, endurance athletes demonstrated a very strong relationship to ankle peak moment ($r=0.739$; $p=0.015$). Results also revealed a strong negative relationship to knee touchdown angle and leg stiffness ($r=-0.592$; $p=0.071$) and a moderate relationship between hip angular displacement and leg stiffness ($r=-0.390$; $p=0.265$).

Table 7.4- *Stiffness Control Mechanisms and their Relationship with Leg Stiffness during Repetitive Hopping Assessment. Values are mean (SD).*

Repeat Jumps	Control (*n*=14)	Control Relationship to Kleg (r)	Netball (*n*=20)	Netball Relationship to Kleg (r)	Endurance (*n*=13)	Endurance Relationship to Kleg (r)
Leg Stiffness (N·m^{-1}·kg^{-1})	96.08 (19.58)[bc]		139.88 (27.96)[a]		154.23 (29.05)[a]	
Jump Height (m)	0.049 (0.021)[bc]		0.117 (0.040)[a]		0.089 (0.031)[a]	
Hip Stiffness (N·m^{-1}·deg^{-1}·kg^{-1})*	-0.020 (0.137)	-0.350	-0.006 (0.175)	0.103	0.097 (0.286)	0.161
Hip Peak Joint Moment (N·m^{-1}·kg^{-1})	0.43 (1.64)	0.013	0.97 (1.50)	0.133	1.50 (0.48)	0.179
Hip Angular Displacement (deg)	11.47 (3.50)	-0.205	9.97 (3.73)	-0.455[d]	8.26 (3.68)	-0.390
Hip Touchdown Angle (deg)	11.65 (2.42)[c]	0.309	17.55 (7.78)[a]	0.275	22.56 (4.43)[a]	-0.055
Knee Stiffness (N·m^{-1}·deg^{-1}·kg^{-1})	0.112 (0.052)	0.040	0.132 (0.046)	0.519[d]	0.106 (0.032)	0.011
Knee Peak Joint Moment (N·m^{-1}·kg^{-1})	2.14 (0.72)[b]	0.192	3.28 (0.95)[ac]	0.357	2.17 (0.89)[b]	0.025
Knee Angular Displacement (deg)	25.19 (6.23)	-0.100	30.05 (7.05)	-0.407	24.41 (3.08)	-0.054
Knee Touchdown Angle (deg)	20.12 (5.27)	0.176	21.46 (4.33)	0.203	23.22 (4.85)	-0.592
Ankle Stiffness (N·m^{-1}·deg^{-1}·kg^{-1})	0.066 (0.018)[c]	0.505	0.077 (0.018)	0.449[d]	0.086 (0.007)[a]	0.798[d]
Ankle Peak Joint Moment (N·m^{-1}·kg^{-1})	2.50 (0.60)[bc]	0.759[d]	3.23 (0.52)[a]	0.793[d]	3.19 (0.76)[a]	0.739[d]
Ankle Angular Displacement (deg)	39.28 (5.80)	0.251	44.33 (7.18)	0.097	38.75 (6.29)	-0.069
Ankle Touchdown Angle (deg)	-15.71 (6.28)	-0.237	-20.20 (7.59)[c]	-0.246	-12.24 (5.96)[b]	0.102

[a] Significantly different to control group; [b] Significantly different to netball group; [c] Significantly different to endurance group; [d] Significant correlation ($p<0.05$); * Non parametric Kruskal-Wallis test implemented; – negative ankle touchdown angles indicates plantar-flexion.

The PCA analysis investigating joint stiffness contributions to leg stiffness revealed that PC 1 and 2 explained 76.98% of variance for the sprint, 64.72% for sidestep cutting and 81.17% for the repetitive hopping task (Table 7.5). Visual inspection of the bi-plots indicated that the athletic populations clustered around specific joint contributions during the sprint and sidestep cutting tasks. Specifically, endurance athletes gathered around hip stiffness and netball athletes grouped around knee and ankle stiffness, while the control group displayed no clear strategy (Figure 7.1 and 7.2). The repetitive hopping task displayed results similar to the sport specific tests, where the control group displayed no clear strategy. In contrast netball athletes utilised knee and ankle stiffness, while endurance athletes appeared to rely on stiffness of the ankle (Figure 7.3).

Table 7.5- *Weighted Principal Component Analysis Assessing Leg, Hip, Knee and Ankle Stiffness. Values are Percentage (%) of the Variance explained by each principle component.*

Principal Component	Sprint	Sidestep Cutting	Repetitive Hopping
PC 1	39.43%	43.35%	47.97%
PC 2	25.29%	33.63%	33.20%
PC 3	22.76%	14.88%	11.65%
PC 4	12.53%	8.14%	7.17%

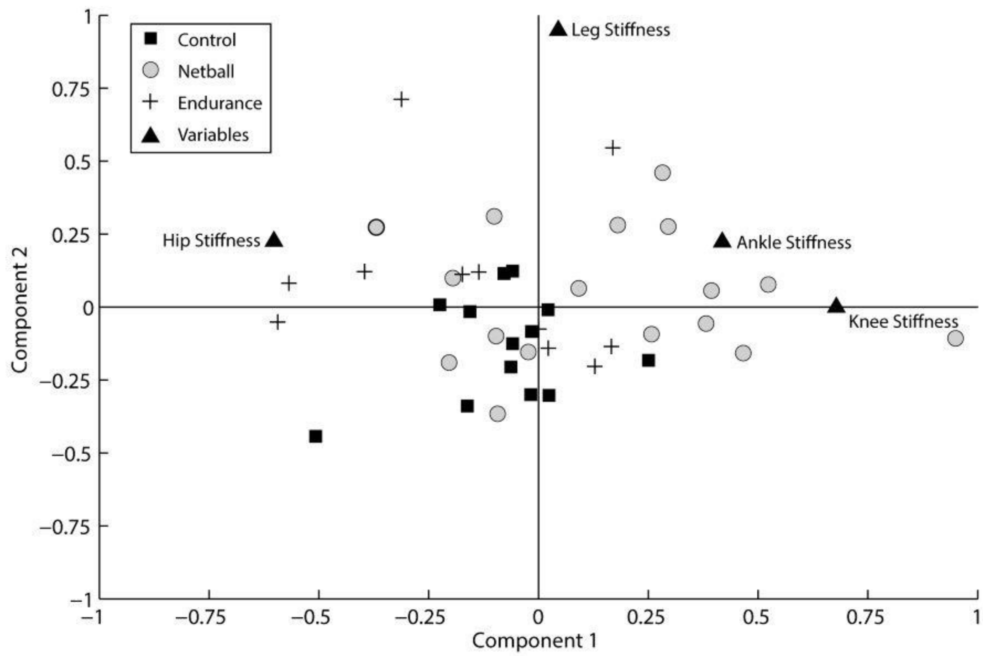


Figure 7.1- Bi-plots of the first and second principal components evaluating the interaction of leg and joint stiffness during sprinting. Utilised for visual inspection to assess participant group clustering about dominant variable.

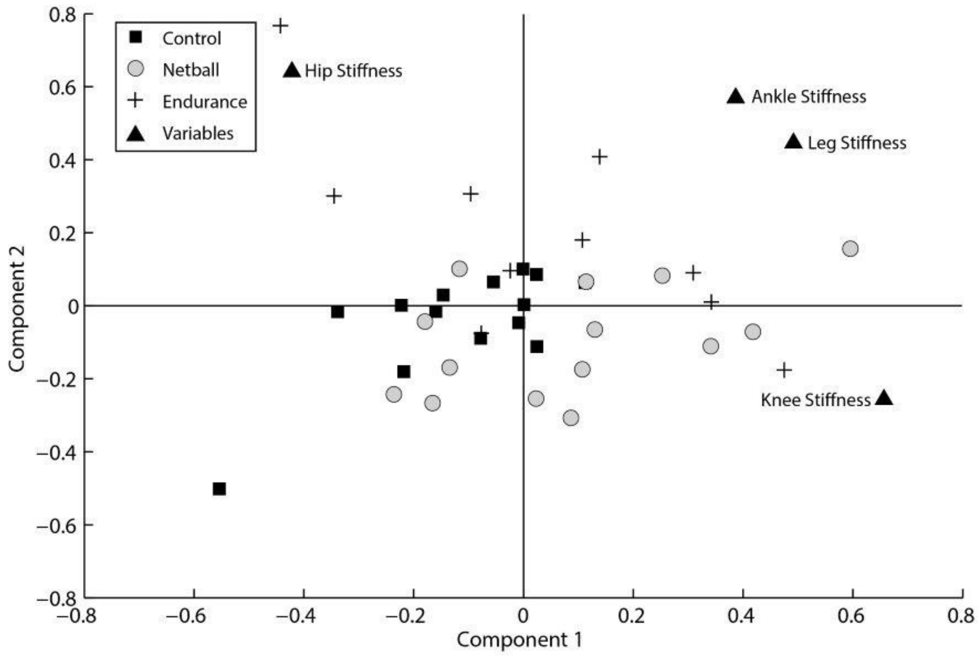


Figure 7.2- Bi-plots of the first and second principal components evaluating the interaction of leg and joint stiffness during anticipated change of direction cutting task. Utilised for visual inspection to assess participant group clustering about dominant variable.

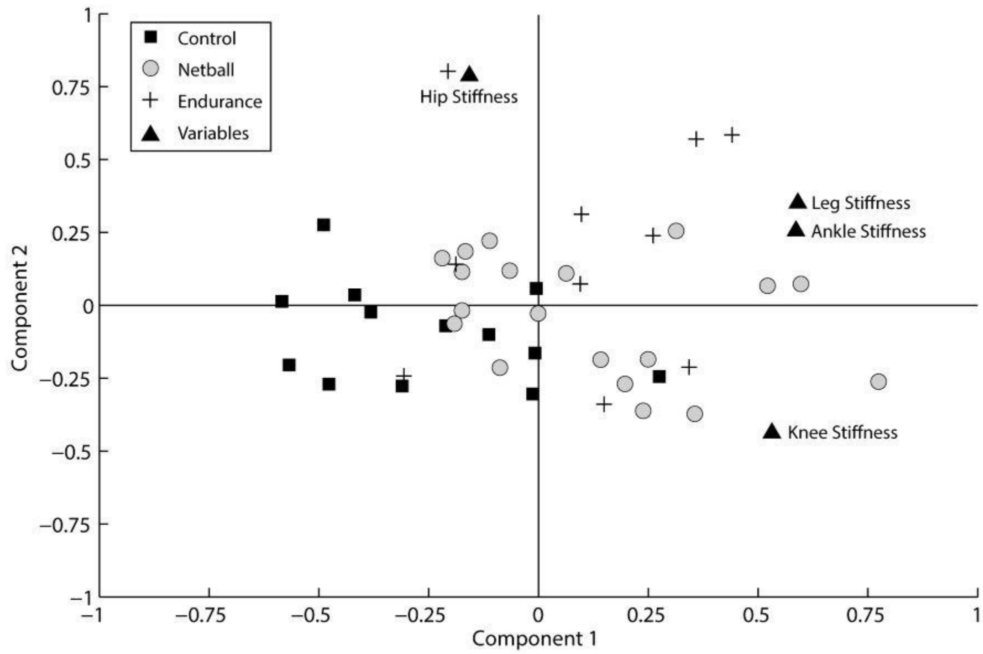


Figure 7.3- Bi-plots of the first and second principal components evaluating the interaction of leg and joint stiffness during repetitive hopping. Utilised for visual inspection to assess participant group clustering about dominant variable.

7.5 Discussion

The present study investigated leg stiffness, joint stiffness and the contributory kinematic and kinetic stiffness modulation strategies female athletic populations utilise to meet the demands of dynamic and sports-specific tasks. Leg stiffness, joint stiffness and the contributory mechanism differences were observed between groups across all investigated tasks. It's postulated these differences are due to varying style of training and conditioning between the evaluated populations.

In congruence with previous research evaluating sports-specific tests of stiffness, the results of this study indicated that endurance athletes displayed a stiffer leg spring than netball and control groups (See Chapter 6). Furthermore, both athletic groups displayed higher stiffness than the control group during the repetitive hopping task (Hobara, Kimura, et al., 2010). The training and competition demands of endurance athletes lead to higher levels of stiffness to maximise running efficiency through minimised flexion of the joints and vertical oscillation of the centre of mass (Bushnell & Hunter, 2007; Hobara, Kimura, et al., 2010). These intrinsic adaptations to chronic training may contribute to endurance athletes displaying inherently higher levels of stiffness across all evaluated tasks. In comparison to the control group, netball athletes displayed higher stiffness during the repetitive hopping tasks presumably due to adaptations to repeated bouts of sub-maximal intensity. While the netball group did not display stiffness differences during the sports-specific tests, previous research has theorised that netball athletes are able to effectively optimise stiffness to meet task demands, particularly during anticipated change of direction tasks where higher levels of stiffness appear to be detrimental to performance (See Chapter 6). Although the results appear to indicate stiffness modulation of the investigated athletic groups reflects adaptations resulting from chronic training, the control group displayed lower levels of stiffness speculated to be attributed to a lack of specific neuromuscular adaptations to effectively meet the demands of the evaluated tasks.

Unlike the endurance and control groups, netball athletes are accustomed to performing repeated sprints, rotational movements about a joint and vertical jumps aiming to achieve maximal vertical distance. The results revealed that this population utilised similar joint modulation strategies to meet performance demands across all evaluated tasks. Findings for the tasks classed as sports-specific (sprint and anticipated change of direction) generally indicated that netball athletes displayed a stiffer knee joint and higher knee flexion angles at touchdown than both endurance and control groups. Furthermore, netball athletes exhibited higher peak ankle moments compared to the control group across all three tasks and higher peak moments at the knee when compared to both groups during the change of direction and repetitive hopping tasks. The optimisation of kinematic and kinetic mechanisms, particularly higher ratios of joint stiffness at the knee and ankle, are essential for efficient locomotion and shortened ground contact necessary for performance enhancement (Arampatzis et al., 1999; Kuitunen, Komi, et al., 2002). The PCA results of all tasks further reflected this concept where netball athletes appeared to utilise key contributions from knee and ankle stiffness in the driving of leg stiffness. Research has suggested that joint stiffness plays a key role in modulating leg stiffness, however chronic athletic training appears to influence joint stiffness, neuromuscular control and intrinsic stiffness of muscle fibres which are of importance in generating stiffness (Hobara, Kimura, et al., 2010). As noted, knee stiffness plays a key role in running performance (Arampatzis et al., 1999), while ankle stiffness is essential for optimal jumping performance (Millett et al., 2015). These tasks are common movements in the training demands of netball athletes, subsequently influencing the modulation strategies of this population to rely on stiffness contribution from knee and ankle stiffness. The knee and ankle joints play important roles in the attenuation of mechanical load for netball athletes to meet the performance demands of their sport. It can be speculated this is a possible contributory factor in the mechanisms influencing higher injury incidences at these joint sights for this particular athletic population (McKay, Goldie, Payne, Oakes, & Watson, 2001), however this concept requires further investigation. Furthermore, the results of this study further support the assumption that netballers utilise the knee and ankle joint to achieve optimal performance, where higher levels of stiffness were derived from minimal angular displacement, reduced flexion at touchdown and higher peak moments at these joints.

Athletic training affects the kinetic and kinematic movement strategies of athletes, subsequently influencing the lower limb stiffness modulation and optimisation that athletes employ to meet task demands (Ambegaonkar et al., 2011; Kuitunen, Avela, et al., 2002; Kuitunen et al., 2007; Kuitunen et al., 2011). During the sprint task netball athletes approached contact with higher hip touchdown angles and a neutral foot position, which may allow for a more effective ground contact and forward velocity. In turn this provided higher ankle stiffness and rigidity around the knee joint during ground contact when compared to the endurance and control groups, which enhanced mechanical efficiency during locomotion. In contrast during the change of direction cutting task netball athletes displayed increased compression in the leg spring in order to achieve a controlled landing and diagonal push to the side at high velocity, evident through increased hip and ankle angular displacement. It can be speculated this contributes to lower leg stiffness, optimal for rotational change of direction tasks where higher levels of stiffness appear to be detrimental to performance in netballers (See Chapter 6). This concept is similar to leg stiffness changes displayed during higher drop jump heights (Walshe & Wilson, 1997). In comparison to the sports-specific tasks, netball athletes displayed higher hip flexion angles at contact than the control group and increased angular displacement at the knee than both endurance and control groups during hopping. Netball athletes appear to display effective modulation of the mechanical strategies to achieve optimal performance during the repetitive hopping task evident through higher jump heights. Results appear to indicate that the chronic training patterns of netball athletes influences the kinematic and kinetic movement strategies athletes employ to optimise stiffness to meet the demands of the task, however the longitudinal impact of training on movement strategies employed by certain athletes, along with the associated implications for injury risk requires further investigation.

Inspection of the modulation strategies utilised by endurance athletes during dynamic and sports-specific tests suggests that athletes approach contact with a straighter ‘stiffer’ lever and less joint angular displacement, subsequently allowing for higher stiffness to be achieved. These findings were highlighted in the sprint task where athletes exhibited less hip angular displacement and approached contact with decreased flexion angles at the knee when compared to netball athletes. Visual inspection of PCA bi-plots highlighted endurance athletes utilise stiffness contributions of the hip to optimise stiffness of the leg spring. It is known the hip plays an important role in running gait of track and field athletes where links have been established between increased output of the hip extensor muscles and increased running speed (Kuitunen, Komi, et al., 2002; Williams, 2000). Increased work and power produced by the hip extensors assists in allowing for a stiffer knee and ankle joint which may shorten ground contact time and improve mechanical efficiency of locomotion, which is of necessity for endurance athletes who strive to maximise running economy to reduce energy expenditure (Kuitunen, Komi, et al., 2002). Optimal pre-activation of hip extensor muscles allows for effective hip drive. To achieve higher running speeds maximal hip flexion is necessary to allow for an effective ground contact, optimal propulsion and appropriate foot contact position (Williams, 2000). The current results displayed these characteristics where endurance athletes exhibited higher hip flexion angles and neutral foot position at contact when compared to the control group who approached with greater levels of dorsi flexion. Although endurance athletes displayed lower knee and ankle stiffness, greater knee angular displacement and lower ankle peak moments than the investigated netball athletes, the results suggest that netballers modulate stiffness through contributions of the knee and ankle joint. As a result, it can be speculated that variations in ratios of joint stiffness occur between athletic populations as a result of chronic training differences which influence the pre-activation and ultimately the behaviour of the joint through range of motion and velocity.

It was speculated endurance athletes achieved inherently higher stiffness during the change of direction cutting task as a consequence of neuromuscular adaptations to chronic training where minimised joint displacement at the hip and knee appeared moderately related to higher levels of stiffness. In addition, endurance athletes exhibited less displacement at the hip than netball athletes, suggesting endurance athletes utilise limited hip displacement to stiffen the leg spring. These findings were in line with previous research investigating endurance athletes which highlighted minimised joint flexion angles contributing to minimal vertical oscillation of the centre of mass and consequently higher levels of stiffness (Bushnell & Hunter, 2007; Hobara, Kimura, et al., 2010). As this population is unaccustomed to rotational movements about a joint, they appear unable to effectively optimise stiffness to meet the demands of the task and as a result utilise kinematic and kinetic modulation strategies representative of their typical training and competition requirements. Furthermore, this notion was reflected in the PCA analysis where endurance athletes appeared to utilise hip joint stiffness contributions in order to modulate leg stiffness. These findings were similar to the results of the sprint task, reflective of normal training and competition demands of endurance athletes.

Additionally, endurance athletes approach contact with decreased knee flexion in order to implement a rigid leg spring. In contrast, as previously noted netball athletes utilise knee stiffness contributions and as a result subsequently display higher stiffness at the knee. Endurance athletes appeared to implement a stiffer hip and higher hip and ankle peak moments subsequently achieving higher stiffness than the control group. This suggests that although endurance athletes may not be able to effectively optimise stiffness, their training allows them to perform the task more efficiently than controls. Similar to the sprint task, both athletic groups approached contact with higher plantar flexion angles than the control group indicative of a more active ground contact to achieve the push phase of change of direction task.

Results of the repetitive hopping task displayed similar findings to the sprint and change of direction cutting tasks, whereby endurance athletes utilised a stiffer leg spring to meet the demands of the task. It appeared this population implemented kinematic strategies similar to those identified during the sports-specific tests, where athletes displayed higher hip flexion angles at contact than the control group, to allow for effective ground contact thus achieving greater jump heights. Comparatively endurance athletes displayed a stiffer spring to achieve performance demands and higher levels of stiffness, displaying less knee angular displacement than netball athletes and higher ankle stiffness than controls. It is speculated joint stiffness differences occur as a result of training influences on intrinsic stiffness of tendinous tissues. Research has established endurance athletes display higher ratios of slow-twitch muscle fibres known to possess greater dynamic stiffness, consequently allowing endurance athletes to achieve higher levels of leg stiffness when compared to untrained ‘controls’ (Hobara, Kimura, et al., 2010). These findings were in line with the outcomes of this study. Furthermore, results were in line with additional findings which suggested higher ratios of ankle moments were evident in endurance athletes when compared to a control group allowing for a stiffer ankle joint (Hobara, Kimura, et al., 2010). Endurance athletes utilised less hip angular displacement, less knee flexion at touchdown, a stiffer ankle joint, less plantar flexion at contact and higher ankle peak moments in order to achieve a stiffer lever and subsequently higher stiffness. These findings were consistent with the results of sports-specific tests. In line with previous research, PCA results established that knee and ankle stiffness were key contributors in stiffness modulation during repetitive hopping (Farley & Morgenroth, 1999). Across all evaluated tasks the results of this study indicated endurance athletes displayed a stiffer spring and higher leg stiffness, which are known to be associated with the incidence of high impact injuries (Butler et al., 2003; Hobara, Kimura, et al., 2010). Higher stiffness combined with higher training loads may increase injury risk in athletes, however further investigation is required (Butler et al., 2003; Hobara, Kimura, et al., 2010).

The results of this study established that athletic training strongly influences the kinetic and kinematic movement patterns of athletes. These movement patterns are specific to each athletic population where athletes attenuate leg stiffness, joint stiffness and the contributory mechanical mechanisms in accordance with the performance requirements of their typical daily training. Unlike the athletic groups, control populations appear to lack common modulation strategies needed to meet the performance demands of the evaluated tasks. The control group displayed less hip drive necessary for effective ground contact, greater joint displacement and lower peak joint moments, consequently achieving lower levels of leg and joint stiffness necessary for enhanced performance. PCA analysis revealed the control group as a collective displayed no dominant joint in stiffness modulation, indicating stiffness attenuation for untrained individuals appears to be an individualised approach. Findings suggest individuals who do not partake in specific training may lack the necessary neural adaptations required for optimal leg and joint stiffness modulation and as a result utilise an inconsistent technique to meet task demands (Millett et al., 2015).

Recent research investigating netball and endurance athletes identified a moderate relationship between leg stiffness during sports-specific tests and repetitive hopping. This suggests that repetitive hopping may serve as an intermediate stiffness performance and injury monitoring tool for practitioners in elite sport (Millett et al., 2015). The findings of this study indicate that athletic populations utilise similar mechanical modulation strategies within sports-specific tasks as during hopping. It is known stiffness modulation is reliant upon the task requirements and the individual's training background, ultimately influencing the kinematic and kinetic modulation strategies athletes employ due to neuromuscular response and adaptations to training (Komi, 2000). Although repetitive hopping is a dynamic task, it appears that the performance demands elicited are not equivalent of sports-specific tasks. Despite results indicating similar underlying stiffness modulation strategies between repetitive hopping and sports-specific tasks, it can be speculated that a stronger relationship may not be evident as the stiffness control mechanisms may not completely reflect training and competition demands. The results of this study appear to indicate chronic athletic training has a strong influence on joint control strategies athletes utilise, where modulation strategies are specific to each individual athletic population. Results of this study, along with previous research, indicate that athletes implement similar stiffness control strategies specific to their training background, potentially due to neuromuscular adaptations to training, during discrete jumping tasks and functional sports-specific tasks (Hobara, Kimura, et al., 2010; Millett et al., 2015). Research has also established that endurance and netball athletes display similar dominant joints during basic jump tasks to those identified in this study, although it seems that leg stiffness is unrelated between basic jumping tasks and sport specific tasks (Millett et al., 2015, 2016). Although a common joint strategy is implemented, a stiffness relationship may not be evident between these tasks as the demands of the movement do not require athletes to implement all the mechanisms relevant to their training demands. As the repetitive hopping task is more dynamic than a basic jumping task it allows for an athletes' modulation strategies to be similar however does not completely represent the kinematic training response of higher demanding tasks representative of an athlete's training and competition background. Furthermore, the control group displayed no common strategy between tasks and as a result no stiffness relationships were observed.

7.6 Practical Applications

Understanding the kinematic and kinetic stiffness modulation strategies athletes utilise during training and competition is of importance to gain insight into the influence of chronic athletic training on leg and joint stiffness. Results of this study established a clear training influence on these modulation strategies that appear to be specific to each athletic population. Insight into the kinematic and kinetic modulation strategies athletic populations employ to meet the demands of their sport may be a contributory factor to specific predispositions to particular injury incidence within athletic populations. However, this notion requires further investigation to gain knowledge of the longitudinal impact of chronic athletic training on the stiffness modulation mechanisms and how these may contribute to injury risk and performance enhancement.

7.7 Acknowledgments

The authors would like to thank all participants, coaches and the New South Wales Institute of Sport Netball program for their participation and support during this study.

7.8 Summary and Key Findings

Chapter 7 established how chronic athletic training influences the stiffness modulation strategies athletes utilise to meet task demands. Results indicate athletes employ joint control strategies that appear specific to their athletic training background. Although similar joint control strategies are observed between basic jumping tasks and sports-specific tasks, results highlight sports-specific tasks as superior screening tools. Athletes display similar control strategies during both hopping and sports-specific tasks, however only a moderate relationship between these tasks was observed. Despite this, it appears repetitive hopping may still serve as an intermediate monitoring tool however caution in the interpretation of results is recommended.

7.9 Recommendations for Future Research

Chapters 6, 7 and 8 established chronic athletic training appears to have a strong influence on leg stiffness, joint stiffness and the contributory stiffness control mechanisms. In athletic screening and monitoring, sports-specific and dynamic hopping tasks appear to be the most appropriate tasks to utilise. However, there remains a need to understand the longitudinal leg stiffness changes that occur as a result of chronic training and the associated injury risk. There is a need to also explore the appropriateness of tasks in their ability to identify injury risk.

7.10 Importance of Chapter 8

Chapter 6, 7 and 8 highlighted the need to understand the longitudinal stiffness changes that occur as a result of chronic athletic training to increase existing knowledge regarding the associated injury risk to athletes. Increased understanding of the links between stiffness and injury during sports-specific tasks may allow for early identification of at risk athletes and early implementation of preventative strategies.

Chapter 8 evaluated Aim 4 of the thesis:

Aim 4 – To assess the longitudinal differences across a season of training (pre, post and off season) in leg stiffness in different female athletic sub-populations from varied training backgrounds during repeated hopping and sports-specific tasks. Additionally, to prospectively evaluate the associated lower-body injury risk in athletes.

Chapter 8. Study 4: Longitudinal Lower Body Stiffness Variations and Associated Injury Risk During Sports-Specific Tasks in Well Trained Female Athletes

8.1 Abstract

Stiffness of the lower limb quantifies the relationship between the amount of leg flexion and the applied external load to the limb. The study aimed to investigate leg stiffness changes during dynamic and sports-specific tasks across a season of training and the associated injury risk in female athletes. Thirty-nine female participants (15 nationally identified netballers, 12 high level endurance athletes and 12 age and gender matched controls) completed a sprint, anticipated sidestep cutting and a unilateral repetitive hopping task. Leg stiffness was derived from data captured with a 10 camera motion analysis system and force plate during pre-season, post-season and off-season tests. Statistical analysis evaluated leg stiffness differences across the season and assessed prospective injury risk. Sports-specific tasks identified significant differences in leg stiffness across the season in athletic populations ($p=0.005-0.042$). Variations in leg stiffness were also evident between the uninjured, soft tissue injury and overuse injury groups ($p<0.001-0.039$). Furthermore, results of the injury risk prediction model indicated tasks relevant to training background predicted soft tissue and overuse injury risk within netball and endurance athletes. Chronic athletic training appears to influence how athletes optimise stiffness across a season to meet performance demands and is related to injury risk. It appears functional sports-specific tasks are able to accurately identify and monitor longitudinal stiffness changes in athletes.

KEYWORDS Leg stiffness; athletic training; long term changes; sprinting; change of direction; hopping

8.2 Introduction

Stiffness of the lower limb quantifies the relationship between the amount of leg flexion and the applied external load subjected to the limb (Brughelli & Cronin, 2008a, 2008b). Lower limb stiffness can be described through the spring-mass model, where the displacement of the centre of mass during ground contact is examined relative to the ground reaction force (Brughelli & Cronin, 2008b; Slawinski et al., 2008). Optimising stiffness can assist the joint or limb to resist change under an applied force, allowing for enhanced storage and return of elastic energy necessary for peak performance (Butler et al., 2003; Komi, 2000).

Research has established that stiffness is linked to both performance and injury risk (Ambegaonkar et al., 2011; Comyns et al., 2007; Hobara, Inoue, et al., 2010; Hobara, Kimura, et al., 2010; Laffaye et al., 2005; Watsford et al., 2010), where higher levels of stiffness are associated with an elevated risk of overuse, bone related injuries (Butler et al., 2003; Hobara, Kimura, et al., 2010). In contrast, lower levels of stiffness appear to be related to increased risk of soft tissue injuries such as muscle tears and strains (Butler et al., 2003). Athletic training may assist in the development of key lower limb and joint stiffness modulation mechanisms of the musculoskeletal system such as neuromuscular control and the co-contraction and regulation of muscle activity (Ambegaonkar et al., 2011; Kuitunen, Avela, et al., 2002; Kuitunen et al., 2007; Kuitunen et al., 2011). Training load and intensity is manipulated and varies within chronic athletic training, placing varied demands on an athlete's system. It has been theorised an optimal range of lower limb stiffness exists to allow for optimal performance and minimisation of injury risk to athletes and that as training load and intensity increases this range narrows (Butler et al., 2003). As the potential low risk zone narrows, athletes are conceivably at an increased risk of injury incidence if they fall outside the optimal range (Butler et al., 2003). Few studies, however, have evaluated the longitudinal changes in lower limb stiffness to gain an understanding of the variations in stiffness across a season of training.

It has been proposed that an athlete's training background or chosen sport may predispose them to an elevated risk of specific types of injuries (Comyns et al., 2007; Hobara, Kimura, et al., 2010; Laffaye et al., 2005). For example, endurance runners may be more susceptible to overuse, bone related injuries due to contributing factors such as elevated levels of lower limb stiffness and high training volumes (Hobara, Kimura, et al., 2010). In high performance sport it is essential to reduce training days lost to injury. Monitoring of lower limb stiffness has the potential to identify injury risk early and implement relevant preventative strategies. However, it remains unclear how stiffness changes over the course of an athlete's training cycle in sports-specific tasks.

In an attempt to understand the longitudinal variance in lower limb stiffness in response to athletic training and its links to injury incidence, research has primarily focused on assessing athletic populations through the use of repetitive hopping tasks (Hobara, Kimura, et al., 2010; Pruyn et al., 2012; Pruyn et al., 2013; Watsford et al., 2010). Research evaluating seasonal changes in Australian Rules footballers during hopping established no significant seasonal stiffness changes, however it was speculated that a significantly higher bilateral stiffness difference was related to soft tissue injury, particularly hamstring tears (Pruyn et al., 2012; Pruyn et al., 2013; Watsford et al., 2010). With potential links between athletic training and stiffness modulation strategies (Bushnell & Hunter, 2007; Hobara, Kimura, et al., 2010), it has been suggested there is a need to consider an athlete's training background when selecting screening tasks to profile and track stiffness of athletes (Millett et al., 2015). Identification of high risk athletes through lower limb stiffness profiling has typically focused on assessing male athletes during basic jumping tasks (Arampatzis et al., 2004; Boullosa et al., 2011; Harrison et al., 2004). Recent research has speculated that discrete maximal effort jumping tasks lack the sensitivity to discriminate stiffness differences between athletic groups and appear unrelated to stiffness measures elicited during sports-specific movements (Millett et al., 2015, 2016). Furthermore, stiffness measures during repetitive hopping appear to be moderately related to stiffness scores during tasks specific to an athletic training background (Millett et al., 2015). However, it is unclear if longitudinal changes exhibited in repetitive hopping represent a similar response to longitudinal stiffness variances reflected in sports-specific tasks. No studies have assessed longitudinal changes in stiffness with the use of sports-specific tasks though the duration of an athlete's training season, particularly in female populations who are known to be at a higher risk of injury incidence when compared to their male counterparts.

Therefore, the purpose of this study was; 1) to investigate the longitudinal differences across a season of training (pre, post and off season) in leg stiffness in different female sub-populations from varied training backgrounds during repeated hopping and sports-specific tasks, and 2) to prospectively evaluate the associated lower-body injury risk to athletes. It was hypothesised that leg stiffness would vary across a season of training and stiffness responses would differ between sub-populations as a result of varied training and conditioning backgrounds. It was also theorised that high levels of stiffness would be linked to overuse injuries and lower levels of stiffness would be associated with soft tissue injuries. Finally, it was hypothesised that injury risk would vary between sub-populations.

8.3 Methods

8.3.1 Experimental Approach to the Problem

This study was a longitudinal prospective study which assessed two sub populations from different athletic training backgrounds along with non-active control participants. Longitudinal changes in stiffness during three tasks reflecting dynamic and sports-specific movements were assessed across athlete's training cycles (pre-season, post-season and off-season) and compared between sub-populations.

8.3.2 Subjects

Based on research assessing stiffness of athletes and non-athletes (Hobara, Kimura, et al., 2010), a moderate to large effect size (0.7) was anticipated for the within-group differences for the primary outcome variable (stiffness). To ensure sufficient statistical power (1-β = 0.8) an a-priori power analysis for F statistics (ANOVA), revealed that a minimum sample size of 12 participants was required in each group (Kraemer & Theimann, 1987). Thirty-nine female participants (15 nationally identified netballers, 12 high level endurance athletes and 12 age matched controls) volunteered to participate in the study (Table 8.1 and 8.2). These populations were targeted to represent differing training and competition demands prevalent in the sporting realm and their reliance on activities involving the stretch-shortening cycle. Netball athletes were representative of a high intensity, intermittent sport requiring maximal jumping efforts, explosive sprints and change of direction, while endurance athletes (1500m – marathon) were identified as their training demands require them to perform continuous running at submaximal intensity with optimal efficiency. Control group participants did not exceed four hours of weekly physical activity. Testing procedures were approved by the Human Research Ethics Committee of the Australian Catholic University. All participants provided written informed consent/parental consent and were injury-free at time of testing. Injury-free was defined as not missing or modifying two consecutive training or competition sessions in the two week period prior to testing (Kirialanis et al., 2003).

Table 8.1- *Participant Descriptive Information and Training Hours Across the Season. Values are Mean (SD).*

Group	N	Age (Years)	Mass (kg)	Height (cm)	Training Years	Training Hours per week Pre-Season	Training Hours per week Pre to Post-Season (5 months)	Training Hours per week Post to Off-Season (3 months)
Netball	15	16.8 (1.0)	70.7 (5.8)	178.0 (6.4)	4.1 (2.2)	5.8 (2.4)	5.8 (2.4)	6.7 (1.1)
Endurance	12	19.8 (4.2)	53.2 (3.0)	166.3 (4.8)	7.8 (2.4)	10.3 (3.4)	10.3 (3.4)	7.3 (3.8)
Control	12	22.3 (2.3)	59.2 (10.7)	163.1 (5.9)	-	1.9 (1.1)	1.9 (1.1)	1.6 (0.8)

8.3.3 Testing Procedures

Participants were asked to attend three testing sessions throughout the duration of their training calendar; 1) immediately prior to the commencement of each athletic population's competition season (pre-season), 2) at the completion of their relevant major championships (post-season) and 3) following a period marked by a cessation or lessening of normal training load (off-season). As control participants did not have specific training phases, duration between test sessions was matched to that of the athletic populations. Participants performed a self-directed dynamic warm up consisting of jogging, and/or cycling and simple lower body dynamic drills. Following a demonstration and a period of familiarisation trials, participants completed five trials of three different tasks reflective of dynamic movements in the daily training environment; a sprint, anticipated sidestep cutting and repetitive hopping. To ensure any order effects did not influence the data, task order was randomised, with the exception of the repetitive hopping task which was performed last to ensure fatigue did not bias results. Participants performed tasks on their dominant leg. Leg dominance was defined using a modified protocol based on the methods of Padua et al. (2006).

8.3.3.1 Sprint

A 40 m sprint was performed by participants at their event competition pace. Force measures and kinematic variables necessary for leg stiffness calculations were collected at 30 m. To ensure trials reflected movement patterns of athletes in the daily training environment participants were discouraged from decelerating or overextending to strike the force plate. Good laboratory intersession stiffness reliability was established for the sprint task (CV 5.6%, ICC 0.96).

8.3.3.2 Anticipated Sidestep Cutting

An anticipated cutting task was included to represent the sharp change of direction cutting movements commonly performed by high intensity intermittent sporting populations. Participants approached the cut with a speed representative of competition pace, landed on the force platform and pushed diagonally sideways to re-accelerate. A target angle of between 30-40 degrees relative to the direction of the contact point of the dominant leg (McLean et al., 2004) was marked on the floor and the non-dominant foot contact immediately following the change of direction was required to fall within this angle range for a valid trial. Adequate laboratory intersession stiffness reliability was established for the anticipated sidestep cutting task (CV 8.2%, ICC 0.95).

8.3.3.3 Repetitive Hopping

Repetitive hopping may serve as a simplistic task where stiffness measures reflect stiffness generated during sports-specific movements (Millett et al., 2015). Participants were asked to perform 27 continuous, reactive hops at a self-selected submaximal intensity. The first five and last two trials were excluded from analysis with the mean of the remaining 20 trials included in subsequent evaluation (Moresi et al., 2014). Target vertical eye heights, ascertained from familiarisation trials, were set at 70% of maximal jump height representative of submaximal intensity to ensure the repeatability and reliability of the hops. Participants were asked to perform the task on their dominant leg and advised to keep their hands positioned on their hips to minimise the contribution of arm swing to jump height (Harman et al., 1990; Luhtanen & Komi, 1979). It is established in the literature that inter-session stiffness reliability for hopping is highly reliable (Typical error of measurement 4.5%; ICC 0.80) (Pruyn et al., 2013).

8.3.3.4 Data Collection

Kinematic data was captured using a ten camera motion analysis system sampling at 500 Hz (Vicon MX; Oxford, United Kingdom). Ground mounted force plates covered with a Mondo track surface sampling at 1000 Hz were used to acquire kinetic data (Advanced Mechanical Technology Inc., Watertown, U.S.A. or Kistler, 9281CA, Switzerland). The standard Vicon Plug-in-gait full body model (Vicon; Oxford, United Kingdom) and associated standardised anthropometric measures were utilised to determine centre of mass displacement (COMd).

8.3.4 Data Analyses

Following analysis of the frequency content and residuals of the power spectra in kinematic data (Winter, 2005), a cut off frequency of 23 Hz for sprint and sidestep cutting and 16 Hz for repetitive hopping was implemented in a dual, low pass, fourth order Butterworth filter. Leg stiffness measures were isolated to the eccentric phase of movement. The eccentric phase of movement was defined as the instance of touchdown to the point where the centre of mass reached maximal vertical displacement during ground contact.

8.3.4.1 Leg Stiffness

Stiffness of the leg spring was determined using the formula presented by McMahon and Cheng (1990). Leg stiffness equates to the peak vertical ground reaction force (PVGRF) divided by leg length change. Change in leg length takes into account the initial leg length of the individual, vertical displacement of the centre of mass, horizontal velocity at impact and contact time (CT). Vertical stiffness calculations are traditionally utilised to assess stiffness during vertical jumps such as repetitive hopping (Brughelli & Cronin, 2008b). However, as sprint and sidestep cutting tasks require leg stiffness calculations to determine stiffness, this methodology was utilised in the evaluation of each task to ensure consistency.

To ensure a typical representation of the individual's leg spring during the sprint and sidestep cutting tasks, the highest and lowest stiffness scores of the five trials were eliminated, with the mean of each participant's middle three scores used in statistical evaluation (Stalbom et al., 2007). Leg stiffness measures were normalised to body mass and standardized to the average population specific pre-season horizontal touchdown velocity (sprint and cutting tasks) or jump frequency (repeat hop task) for all participants using residual calculations derived from population and training phase specific linear regression analysis.

8.3.4.2 Injury Data

In order to determine stiffness changes in response to injury occurrence, participants were asked to complete a self-reported questionnaire pertaining to the nature of the injury, management procedure and duration of training time missed. To assess the association between chronic athletic training, leg stiffness and injury risk, only sports-related lower-body non-contact injuries were included in analysis and isolated to the netball and endurance groups. The control population was excluded from injury analysis. All lower limb sport-related injuries of netball and endurance athletes were pooled together to create an injured group and for further analysis were also separated into two specific classification groups; 1) soft tissue and, 2) overuse. Soft tissue injuries were defined as acute damage to muscle, ligament or tendon and included injuries such as muscle tears and strains (Sports Medicine Australia, 2010). Overuse injuries described injuries that occurred with a gradual onset as a result of repetitive friction, pulling, twisting or compression and represented injuries such as stress fractures/reactions, tendonitis and fasciitis (Sports Medicine Australia, 2010).

8.3.5 Statistical Analyses

Normality was evaluated utilising a critical appraisal approach (Peat & Barton, 2006). Repeated measures analysis of variance with Bonferroni post-hoc tests were calculated to assess longitudinal stiffness changes within each sub-population, injured and uninjured groups. The equivalent non-parametric Friedman test was utilised for cases which violated normal distribution or did not meet sphericity assumptions. Cohen's *d* effect sizes were determined for variables to calculate the distance between mean values through the units of their standard deviations (Cohen, 1988).

Independent t-tests were utilised to evaluate the stiffness differences at each testing phase for the uninjured and injured groups, along with the two injury classification sub-groups. Groups which were not normally distributed were assessed using the equivalent non-parametric Mann-Whitney U test. As two different athletic groups were combined, consideration was given to standardise each population by using individual z scores. However, due to the high incidence of injury in the endurance group biasing the mean and therefore the z score, this method was not used. Additionally, the theoretical model suggests the absolute stiffness value is key to injury risk identification therefore raw scores were utilised in analysis. Investigation into scores established equality between netball overuse injury and endurance overuse injury leg stiffness scores.

Receiver operating characteristic (ROC) curves were utilised to determine a critical cut off threshold in order to evaluate the ability of leg stiffness measures to predict lower limb injury, overuse injury and soft tissue injury risk. Critical cut off threshold values were determined by evaluating values closest to the perfect prediction point (Peat & Barton, 2006). Logistic regression analysis was undertaken to distinguish the ability of the critical cut off threshold to accurately predict injured or non-injured athletes. ROC curve and logistic regression analysis was undertaken on athletic groups separately to determine critical cut off thresholds and injury risk prediction for each task specific to the individual athletic populations. Soft tissue injury risk assessment was inversely coded to ensure low stiffness values indicated soft tissue injury risk.

All statistical analysis was undertaking using the SPSS® (SPSS, v21.0, Inc., Chicago, IL, USA) with an alpha level set at $p<0.05$. Results which displayed p values ranging between 0.05-0.09 and an effect size greater than 0.50 were deemed as providing a clinically meaningful difference (Cohen, 1988; Hopkins, 2005).

8.4 Results

Netballers displayed a significant decline in leg stiffness in sprinting from pre-season to off-season ($p=0.005$) and displayed a clinically meaningful decrease in leg stiffness measures between post and off season measures ($p=0.071$) (Table 8.2). Endurance athletes exhibited significantly higher sprint stiffness post-season scores when compared to off-season ($p=0.021$). Although endurance athletes displayed no significant differences between pre-season and post-season sprint leg stiffness scores, post-season raw scores appeared higher. During the anticipated sidestep cutting task netball athletes displayed a significantly higher leg stiffness score during the off-season when compared to post-season measures (p=0.021) and no change was evident between pre-season and post season leg stiffness scores (p=1.000). In contrast endurance athletes tended to reduce leg stiffness scores in the post-season (p=0.083) and off-season (p=0.083) when compared to the pre-season. Repetitive hopping did not identify any significant differences. However raw leg stiffness scores represented similar patterns between the testing phases as the sports-specific tasks (Table 8.2). No significant leg stiffness differences were evident within the control group across the season in all assessed tasks.

Table 8.2- *Repeated Measures Analysis of Variance Assessing Differences in Leg Stiffness Across a Season of Training in Female Sub-populations. Values are Mean (SD).*

Population	Leg Stiffness	Pre-Season ($N^{-1}\cdot m^{-1}\cdot kg^{-1}$)	Post-Season ($N^{-1}\cdot m^{-1}\cdot kg^{-1}$)	Off-Season ($N^{-1}\cdot m^{-1}\cdot kg^{-1}$)	Pre–Post Effect Size	Pre– Off Effect Size	Post-Off Effect Size
Sprint	**Control**	97.87(20.55)	93.47(14.85)	89.63(18.90)	-0.25	-0.42	-0.23
	Netball [NP]	120.13(26.82)[c]	111.43(29.60)	91.55(18.23)[a]	-0.31	-1.27	-0.83
	Endurance [NP]	128.58(28.72)	138.18(30.76)[c]	124.53(23.70)[b]	0.32	-0.15	-0.50
Sidestep Cutting	**Control** [NP]	92.68(15.24)	93.28(30.76)	83.65(20.35)	0.03	-0.51	-0.38
	Netball	85.52(30.63)	84.09(24.59)[c]	98.49(23.23)[b]	-0.05	0.48	0.60
	Endurance [NP]	136.35(58.65)	122.43(49.61)	107.36(16.25)	-0.26	-0.77	-0.46
Repetitive Hopping	**Control** [NP]	115.73(14.90)	118.78(27.60)	121.81(28.63)	0.14	0.28	0.11
	Netball [NP]	135.47(25.18)	135.23(26.16)	131.47(22.98)	-0.01	-0.17	-0.15
	Endurance	149.14(28.87)	154.30(30.08)	143.77(23.31)	0.18	-0.21	-0.39

Pre, Pre-season; Post, post-season; Off, Off-season; [a] Significantly different to pre-season; [b] Significantly different to post-season; [c] Significantly different to off-season; [NP] Non parametric.

The injury analysis revealed that 63.0% of participants presented with an injury with 29.4% categorised as soft tissue while 70.6% were overuse injuries. Injury incidence separated into sub-populations consisted of 52.9% endurance athletes and 47.1% netball athletes. The majority of the injuries (83.3%) occurred during the competition phase (between the pre-season and post-season testing sessions). Injuries occurred at four locations; lower back (20.8%), hip/upper leg (12.5%), knee (16.7%) and foot/ankle/lower leg (50.0%). Within the netball athletes, 60.0% presented with an injury across the training season. Of these injuries, 63.6% were soft tissue injuries while 36.4% were overuse injuries. Approximately 27.3% of these injuries were reoccurring injuries. Injury incidence in the endurance population revealed 66.7% athletes exhibited an injury. All of the identified injuries were overuse injuries (100%), with 46.2% presenting as reoccurring injuries.

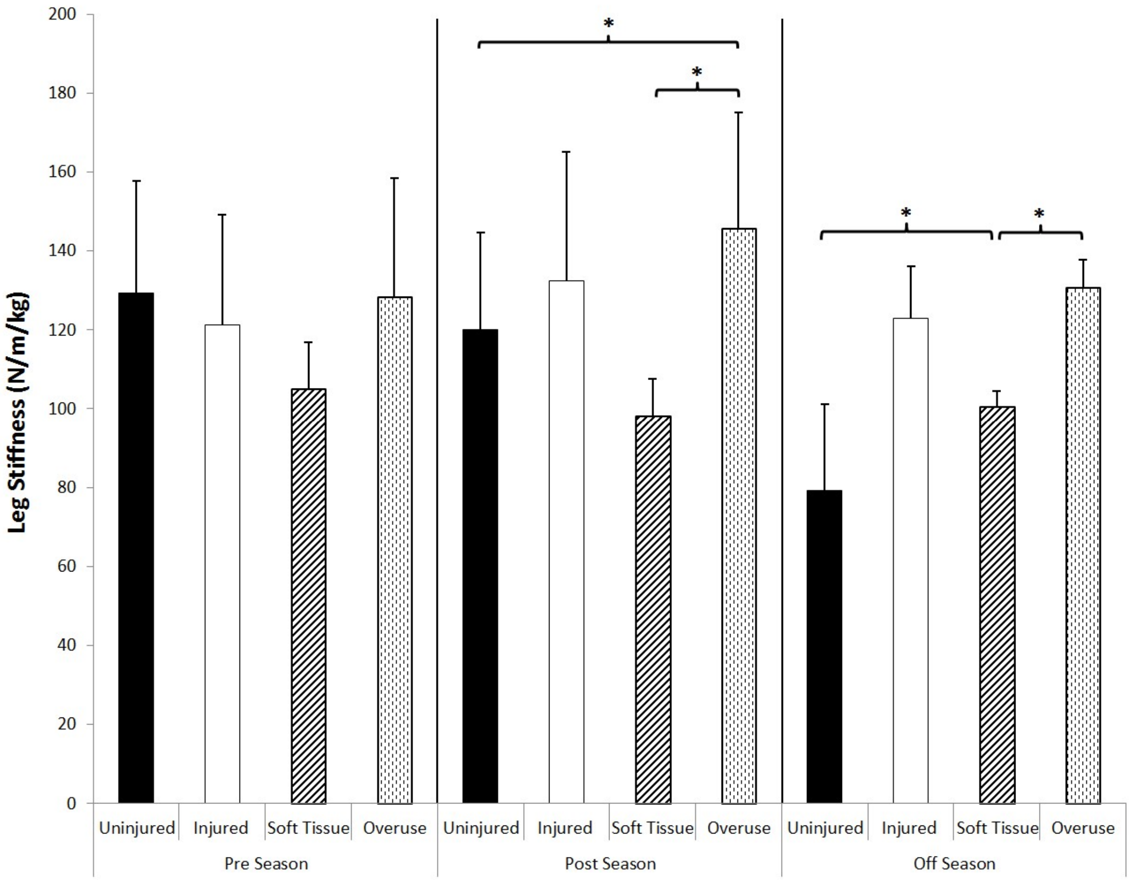
Leg stiffness changes during sprinting across the season revealed that uninjured athletes displayed significantly higher pre-season ($p<0.001$) and post-season ($p<0.001$) leg stiffness scores when compared to the off-season. Injured athletes displayed a significant increase in post-season leg stiffness scores ($p=0.008$) from pre-season measures. When further divided into the two injury classification groups leg stiffness scores did not display any changes across the season for soft tissue injuries, while athletes who presented with overuse injuries displayed a significant increase from pre-season measures to post-season leg stiffness scores ($p=0.021$). The results of the anticipated sidestep cutting task revealed uninjured athletes displayed significantly higher off-season leg stiffness scores ($p=0.019$) when compared to post-season measures. No change across the season was evident in injured athletes or within the two injury classifications of soft tissue and overuse. The repetitive hopping task identified no significant differences across the training season within uninjured or injured athletic populations or the subsequent injury classification groups (Table 8.3).

Table 8.3- *Repeated Measures Analysis of Variance Assessing Differences in Leg Stiffness Across a Season of Training in Uninjured and Injured Groups. Values are Mean (SD).*

		Pre-Season ($N^{-1}·m^{-1}·kg^{-1}$)	Post-Season ($N^{-1}·m^{-1}·kg^{-1}$)	Off-Season ($N^{-1}·m^{-1}·kg^{-1}$)	Pre–Post Effect Size	Pre– Off Effect Size	Post-Off Effect Size
Sprint	**Uninjured** (n=10)	129.36(28.40)^{c}	120.19(24.40)^{c}	79.24(22.06)^{ab}	-0.35	-1.99	-1.76
	Injured ^{NP} (n=17)	121.33(27.84)^{b}	132.45(32.75)^{a}	122.83(13.29)	0.37	0.07	-0.42
	Soft Tissue (n=5)	104.96(11.96)	97.98(9.68)	100.42(4.12)	-0.65	-0.56	0.35
	Overuse ^{NP} (n=12)	128.23(30.11)^{b}	145.68(29.52)^{a}	130.57(7.19)	0.59	0.13	-0.82
Sidestep Cutting	**Uninjured** (n=10)	95.26(33.85)	89.54(28.37)^{c}	109.10(20.47)^{b}	-0.18	0.51	0.80
	Injured ^{NP} (n=17)	115.60(57.95)	115.17(47.04)	102.23(22.83)	-0.01	-0.33	-0.37
	Soft Tissue (n=5)	70.59(18.88)	71.45(3.13)	67.43(2.24)	0.08	-0.30	-1.50
	Overuse ^{NP} (n=12)	130.60(60.52)	131.70(47.55)	113.24(19.57)	0.02	-0.43	-0.55
Repetitive Hopping	**Uninjured** (n=10)	130.84(9.54)	137.09(29.68)	131.54(24.93)	0.32	0.04	-0.20
	Injured (n=17)	146.04(34.00)	144.09(30.02)	142.66(26.53)	-0.06	-0.11	-0.05
	Soft Tissue (n=5)	124.92(7.79)	134.56(11.96)	123.04(3.54)	0.98	0.33	-1.49
	Overuse (n=12)	156.65(37.39)	150.79(34.91)	148.71(30.96)	-0.16	-0.23	-0.06

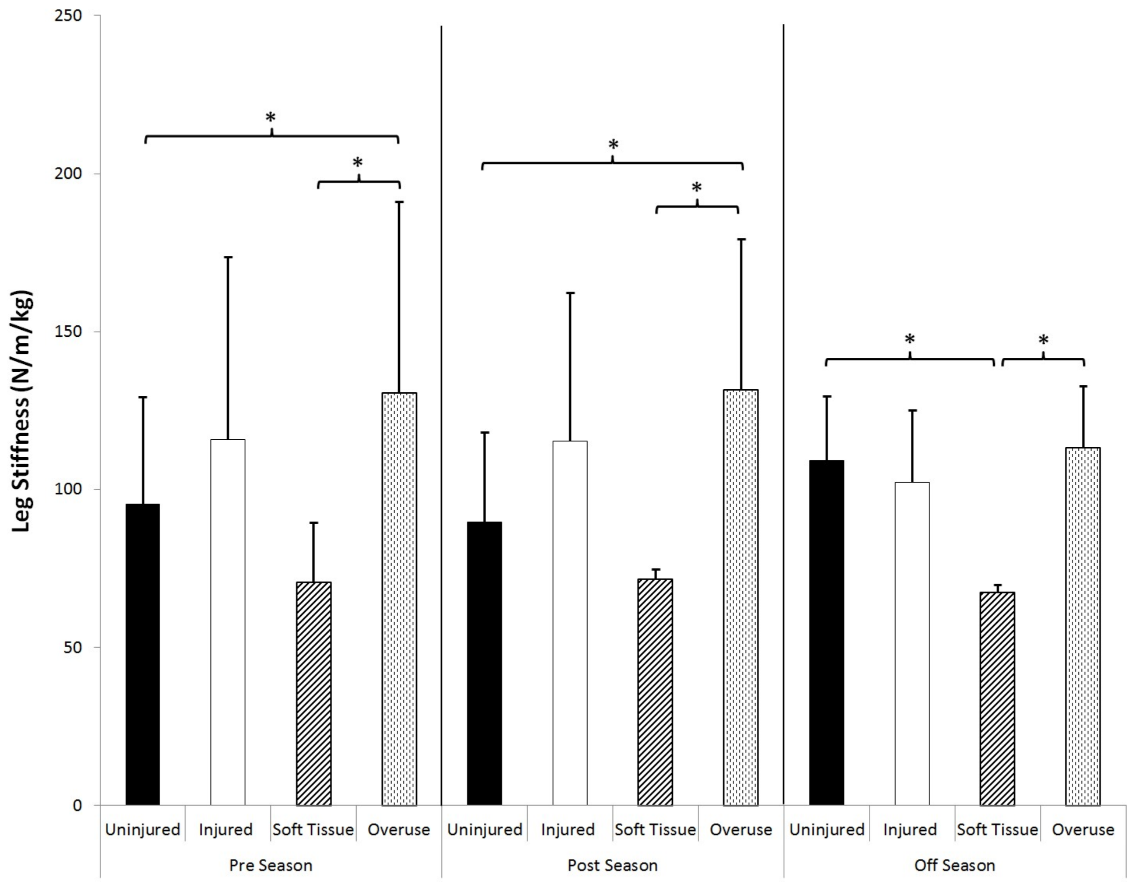
Pre, Pre-season; Post, post-season; Off, Off-season; ^{a} Significantly different to pre-season; ^{b} Significantly different to post-season; ^{c} Significantly different to off-season; ^{NP} Non parametric.

Sprinting results (Figure 8.1) revealed during the pre-season testing a clinically meaningful difference was evident where soft tissue leg stiffness scores were lower than both the uninjured (p=0.093) and overuse (p=0.073) injury groups. Post-season leg stiffness measures revealed the overuse injury group displayed significantly higher scores when compared to the uninjured (p=0.042) and soft tissue groups (p=0.003). A clinically meaningful lower leg stiffness score was observed between the soft tissue group to the uninjured population (p=0.076). Off-season leg stiffness results revealed the soft tissue injury group was significantly lower than the overuse group (p<0.001) and significantly higher than the uninjured group (p=0.015). Anticipated sidestep cutting task results (Figure 8.2) at pre-season indicated the overuse group displayed a significantly higher leg stiffness score when compared to the uninjured (p=0.041) and soft tissue injury (p=0.006) groups. Furthermore, the overuse group displayed higher leg stiffness scores when compared to the uninjured (p=0.010) and soft tissue injury (p=0.002) groups at the post-season. Clinically meaningful differences were also observed where the uninjured group displayed lower leg stiffness scores than the injured athletes (p=0.063) and higher measures when compared to the soft tissue group (p=0.076). The soft tissue injury group displayed significantly lower scores when compared to the uninjured (p=0.001) and overuse (p=0.002) group at off-season. Repetitive hopping t-test results (Figure 8.3) revealed that pre-season leg stiffness scores of the overuse injury group were significantly higher than both the uninjured (p=0.039) and soft tissue injury (p=0.015) group. The injured group displayed a clinically meaningful higher leg stiffness score when compared to the uninjured group. No significant differences were evident between groups at post-season testing. Clinically meaningful lower stiffness scores were evident between the soft tissue and overuse injury groups (p=0.090).



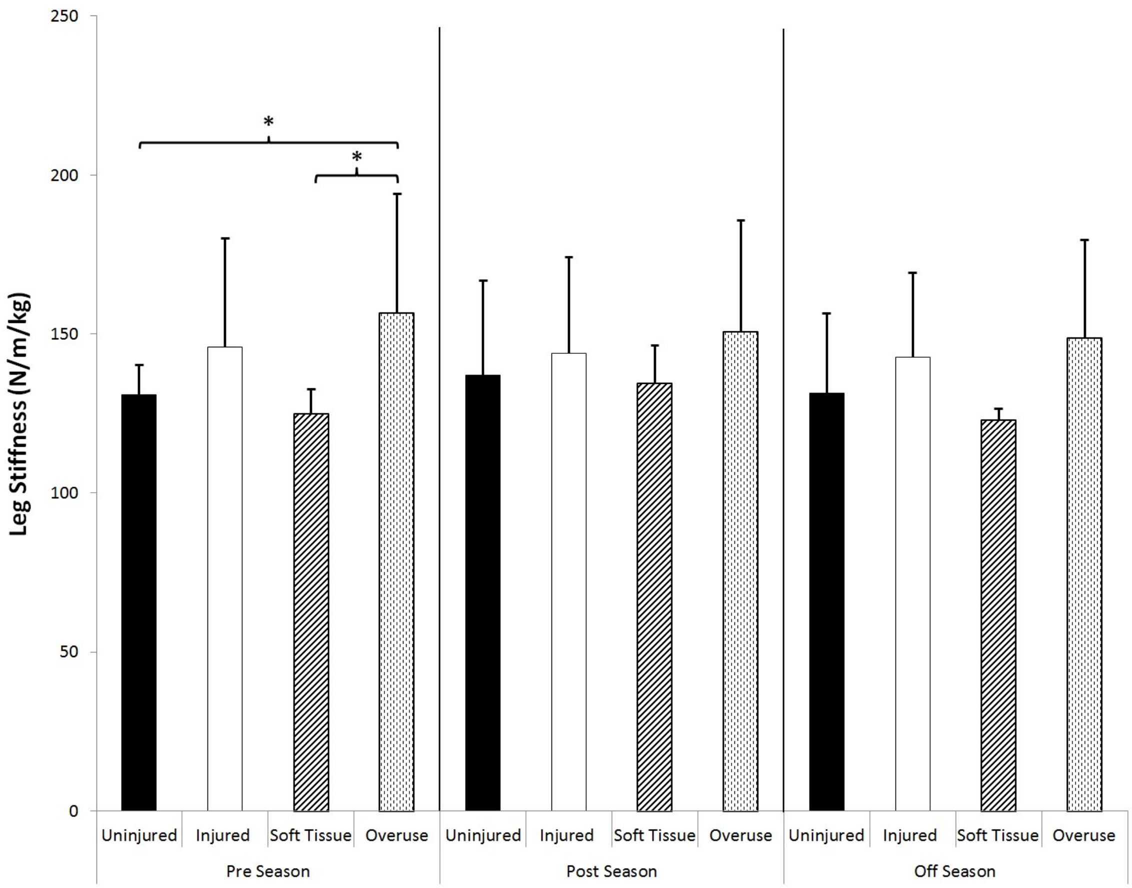
*Significantly different $p<0.05$

Figure 8.1- Differences within injury groups at each testing phase (pre, post and off-season) during sprinting.



*Significantly different $p<0.05$

Figure 8.2- Differences within injury groups at each testing phase (pre, post and off-season) during anticipated side-step cutting.



*Significantly different $p<0.05$

Figure 8.3- Differences within injury groups at each testing phase (pre, post and off-season) during repetitive hopping.

Receiver operating characteristics (ROC) curve results specific to soft tissue and overuse injury groups revealed that the sprint, change of direction and repetitive hopping tasks displayed good sensitivity and specificity, identifying injury risk and non-injury occurrences in netballers (Table 8.4, Figure 8.4 a,b,c). The sprint task also displayed acceptable sensitivity in identifying injury risk in endurance athletes, despite revealing poor specificity for distinguishing uninjured (Table 8.5, Figure 8.4 d).

Table 8.4- *Prospective Injury Prediction Results, Odds Ratio and Receiver Operating Characteristics Curve Results for Injured and Injury Sub-Populations Within Netball and Endurance Athletes*

Uninjured Comparison to Injury Group	Injury Incidence	% Predicted Correctly	Uninjured % Predicted Correctly*	Injury % Predicted Correctly**	Odds Ratio	Confidence Interval (Lower)	Confidence Interval (Upper)	Sig (p value)	ROC Curve Area	Sig (p value)
NETBALL										
Sprint										
Injured	9 of 15	60.0	33.3	44.4	0.400	0.047	3.424	0.403	0.389	0.480
Soft Tissue	5 of 9	66.7	80.0	80.0	16.000	1.093	234.248	0.043	0.840	0.037
Overuse	4 of 9	73.3	81.8	75.0	13.500	0.878	207.624	0.062	0.750	0.151
Cutting										
Injured	9 of 15	60.0	66.7	55.6	2.500	0.292	21.399	0.403	0.556	0.724
Soft Tissue	5 of 9	66.7	70.0	80.0	9.333	0.711	122.570	0.089	0.700	0.221
Overuse	4 of 9	73.3	72.7	100.0	N/A	N/A	N/A	N/A	0.795	0.090
Repetitive Hopping										
Injured	9 of 15	60.0	66.7	44.4	1.600	0.187	13.695	0.668	0.463	0.814
Soft Tissue	5 of 9	66.7	70.0	80.0	9.333	0.711	122.570	0.089	0.760	0.111
Overuse	4 of 9	73.3	81.8	75.0	13.500	0.878	207.624	0.062	0.750	0.151
ENDURANCE										
Sprint										
Injured/Overuse	8 of 12	66.7	50.0	87.5	7.000	0.379	123.347	0.184	0.656	0.396
Cutting										
Injured/Overuse	8 of 12	66.7	50.0	75.0	3.000	0.239	37.672	0.395	0.500	1.000
Repetitive Hopping										
Injured/Overuse	8 of 12	66.7	50.0	50.0	0.333	0.023	4.736	0.417	0.436	0.734

N/A- Result not available. The Odd ratio calculation for this variable was artificially distorted due to relative small numbers of participants and subsequent 100% positive prediction of injured athletes. * - Specificity. ** Sensitivity

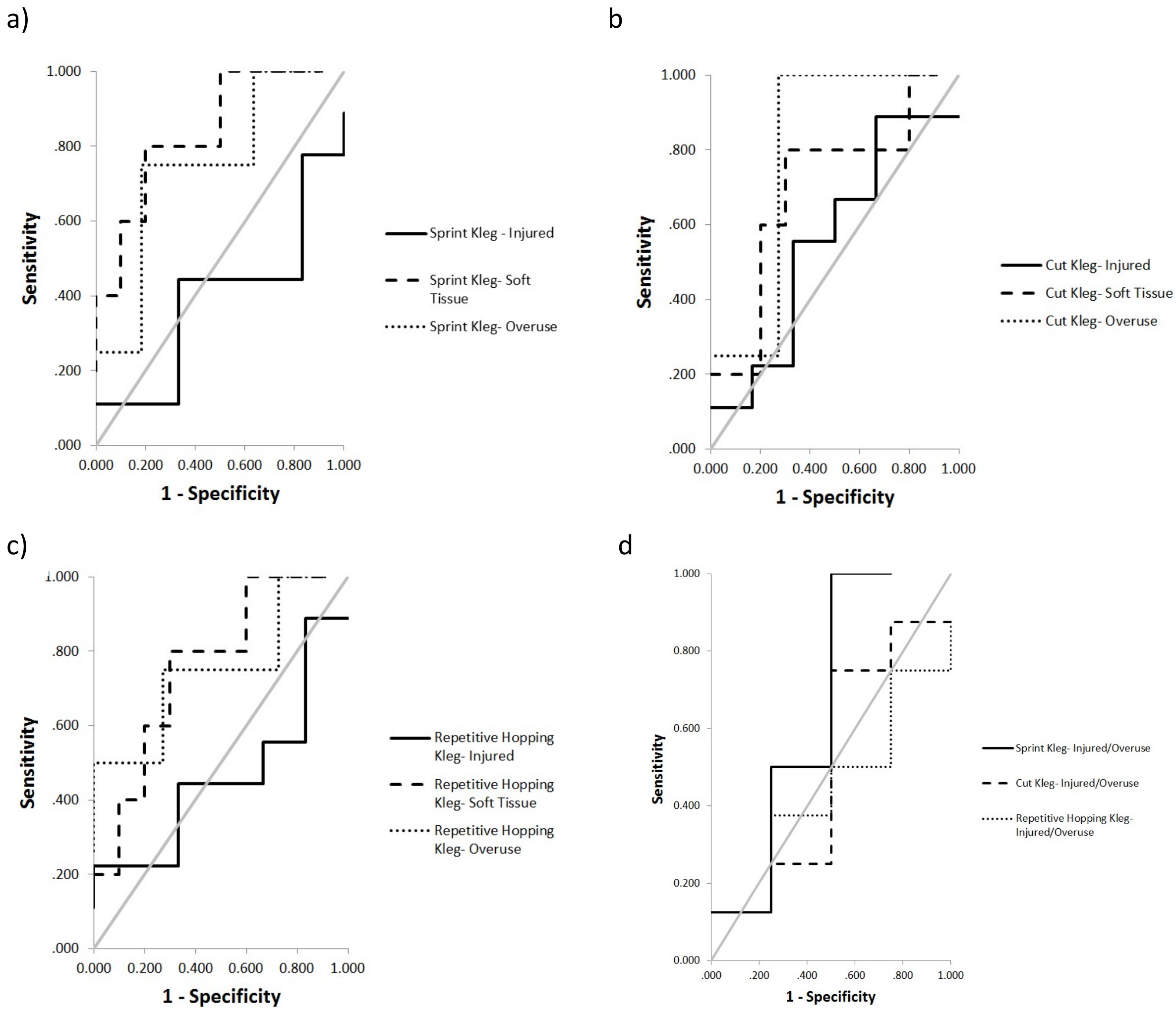


Figure 8.4- Receiver operating characteristics (ROC) results for leg stiffness injury prediction a) Netball Sprint ROC Curve b) Netball Anticipated Side Step Cutting ROC Curve c) Netball Repetitive Hopping ROC Curve d) Endurance ROC Curves.

8.5 Discussion

The present study evaluated the longitudinal changes in leg stiffness across a season of training in female athletes during dynamic and sports-specific tasks, along with the associated injury risk. In congruence with the hypothesis longitudinal changes in stiffness were evident across the season and sports-specific tasks appeared to be superior for identifying stiffness variations and injury risk.

It was anticipated longitudinal changes would be evident across a season of training due to variations in training load, intensity and training demands. Sports-specific results of netballers indicated changes in stiffness across the training cycle. The sprint task revealed that stiffness declined to values lower than pre-season scores by the off-season. It was expected that stiffness would decline during this period as less match-play and general conditioning occurs. Reduced training load and intensity subsequently may reduce muscle strength and adaptation resulting in lower stiffness to meet performance and training demands. The results from the anticipated change of direction cutting task were similar where no change in leg stiffness was observed between the pre-season and post-season scores. In contrast to the sprint task the results established higher stiffness at off season testing. Research has suggested that lower stiffness may be preferred to meet performance demands of high impact reactive tasks, such as a sidestep cutting task, where boundaries may exist for stiffer subjects to modulate high eccentric loads (Walshe & Wilson, 1997) (See Chapter 6). It has been proposed this may be the case for netball athletes as lower stiffness may allow athletes to adequately perform the movement with a controlled soft landing and sidestep with a pushing motion at a high velocity (See Chapter 6). This adaptation to training is typically achieved through greater centre of mass displacement and joint flexion, however this may also present a contributing factor to soft tissue injury incidence in this population. Consequently, it can be speculated that during a period of lower mechanical load and match play, athlete leg stiffness may increase in response to meet the demands of general aerobic fitness resulting in netballers displaying stiffness levels similar to that of their off-season sprint stiffness scores. Furthermore, this stiffness response may also occur due to reduced training and exposure to high velocity rotation movements resulting in optimised stiffness representative of their current training status. No stiffness changes were evident in a population which readily performs high velocity rotational movements about a joint from pre and post-season testing phase. This further reinforces the notion that an optimal lower range of stiffness may be advantageous in change of direction tasks.

Similar to the netball population, endurance athletes displayed a decline in sprint stiffness following a period of reduced training volume. Unlike netball athletes however the stiffness scores of endurance athletes in the off-season returned to levels equivalent to pre-season measures. Recent research has established that endurance athletes displayed higher pre-season stiffness when compared to netball and control populations and subsequently yielded different kinetic and kinematic stiffness modulation strategies specific to their habitual training background (See Chapter 6 and 7). Endurance athletes displayed and maintained higher levels of stiffness with a significantly higher post-season score than off-season. It has been suggested higher levels of stiffness may place athletes at an increased risk of overuse high impact bone related injuries (Butler et al., 2003) making endurance athletes more susceptible to these specific types of injuries (Hobara, Kimura, et al., 2010). Maintaining a high level of stiffness through a critical competition phase (pre to post-season) is key for this population to meet performance demands, as optimal levels of higher stiffness, within limits, are beneficial to optimal performance potentially enhancing storage and return of elastic energy (Butler et al., 2003; Hobara, Kimura, et al., 2010). However, this may place athletes at an increased risk of overuse injuries, a notion also reflected through the injury incidence reports whereby the majority of recruited endurance athletes presented with overuse injuries. In contrast, during the change of direction task, an activity this population is generally unaccustomed to, endurance athletes displayed a progressive decline in stiffness from pre-season measures. Endurance athletes rarely perform high velocity rotational change of direction tasks about a joint. It may be speculated that the seasonal stiffness variations may not be a response to the athletes training status, rather an inherent response to lack of muscular adaptations to effectively modulate stiffness to meet performance demands. The results of this study highlight the notion that chronic athletic training clearly influences stiffness through varying training phases of training load and intensity. Furthermore, it appeared tasks specific to an athlete's training were able to identify longitudinal changes in stiffness, while repetitive hopping did not elicit the same response.

As expected, the control group displayed no change across the assessed time frame in all tasks, it can be suggested no longitudinal variation in stiffness was evident due to the absence of specific athletic training. Research has established that athletic training aids in stiffness optimisation and the underlying mechanisms which contribute to stiffness modulation. Individuals who don't engage in chronic training lack these specific adaptations and are less likely to display stiffness changes as training load does not vary (Millett et al., 2015).

Recent research has speculated that repetitive hopping may serve as an intermediate monitoring tool in high performance sport to track changes in performance and identify potential injury risk (Millett et al., 2015). In line with previous research, the repetitive hopping task did not reveal any longitudinal stiffness changes (Pruyn et al., 2012), despite stiffness variations being evident in sports-specific tasks. Although repetitive hopping indicated no leg stiffness changes, results did appear to follow the same longitudinal stiffness patterns across the season. Repetitive hopping appears to lack the adequate sensitivity or may not induce high enough performance demands to elicit the same significant response as sports-specific tasks. As a result, coaches, researchers and high performance support staff need to take care in interpreting these stiffness results. Furthermore, this study appears to support the notion that there is a clear influence of training on stiffness and it is important that practitioners take an athlete's training background into consideration when identifying screening tools to assess leg stiffness in athletic populations.

Links between lower limb stiffness and injury risk have been established in research, additionally suggestions have been made that an athlete's specific training background may predispose them to specific types of injuries (Butler et al., 2003; Hobara, Kimura, et al., 2010). The results of this study appear to support these notions across all assessed tasks. Similar to the longitudinal assessment of the targeted populations, the sports-specific tasks identified changes in stiffness within injured and uninjured athletic groups. In line with previous research, sprint stiffness results indicated that athletes who presented with soft tissue injury displayed significantly lower stiffness measures than the uninjured at all testing phases, while the overuse injury group displayed significantly higher stiffness than both groups and a significant increase in stiffness at post season (Butler et al., 2003). It can be speculated the musculoskeletal system may be progressively overloaded through a competition phase (pre to post season testing). As stiffness increases through a season this may in turn increase an athletes' exposure to greater forces and mechanical loading, subsequently increasing the stress applied to the lower limb leading to increased risk of overuse injury incidence. Results of this study supported the suggestion that an optimal band range of stiffness exists for athletes, where extreme stiffness scores outside this band range have an increased likelihood of injury incidence, with lower levels of stiffness leading to soft tissue injuries while higher levels of stiffness resulting in overuse injuries (Butler et al., 2003). It's postulated an optimal stiffness 'middle ground' may exist in chronic athletic training across a season to allow for maximal performance outcomes and minimised injury risk. This highlights the potential importance for athletes to adapt or monitor training load according to magnitude changes in stiffness, however acute stiffness fluctuations in response to training load across a season requires further investigation.

Identical to the sprint results, the findings of the anticipated change of direction cutting task supported the theoretical model where higher stiffness scores were associated with overuse injuries, while lower levels of stiffness resulted in soft tissues injuries (Butler et al., 2003). Additionally, the uninjured group displayed a stiffness score in between the two specific injury populations, highlighting the notion an optimal brand range of stiffness may exist to allow for minimised injury occurrence. In contrast to the sprint results, the overuse group displayed no change in stiffness across the season. This may be confounded by the grouping together of both endurance and netball athletes, as endurance athletes are uncustomed to this task and may lack the necessary neuromuscular adaptations (Millett et al., 2015). However, due to a small sample size and a limited number of uninjured athletes in each group, individual athletic population analysis assessing longitudinal changes within separated injury versus uninjured groups was untenable.

Similar to the sports-specific tasks, repetitive hopping was able to identify that the overuse injury group displayed significantly higher stiffness scores than the soft tissue and uninjured group. In line with previous research repetitive hopping was able to identify differences between injured and uninjured athletes, however was unable to discriminate differences across the season within the group (Pruyn et al., 2012). The findings reinforce the notion that this task may not be able to induce the same performance or loading demands to elicit similar response to sports-specific task relevant to an athlete’s habitual training background.

The investigation into the injury risk for individual athletic populations from baseline leg stiffness measures further emphasised the need for practitioners to consider the relevance of the task to the habitual training background of the athlete. Leg stiffness exhibited by netball athletes during sprint, anticipated change of direction and repetitive hopping tasks appeared to adequately prospectively discriminate athletes who presented with lower limb soft tissue and overuse injuries. These tasks also displayed sufficient specificity in predicting uninjured athletes. The results also highlighted the importance for practitioners to treat soft tissue and overuse injury prediction models separately (Moresi, Bradshaw, Greene, & Naughton, 2012). When pooled into one injury group the results were likely to be confounded due to the nature of overuse injuries displaying high stiffness measures and soft tissue injuries exhibiting low stiffness scores (Butler et al., 2003). The stiffness yielded through the sprint task for endurance athletes also sufficiently predicted overuse injuries, while it appeared poor in its specificity to differentiate uninjured athletes. It is important to note there was a high proportion of overuse injuries in this cohort and only a small number presenting with no injuries. Given the small sample size it may be inferred that this task is sufficient in predicting overuse injuries in endurance track and field athletes and is relevant to the demands in their training environment. In contrast, the anticipated change of direction cutting task and repetitive hopping task were relatively poor in their sensitivity to prospectively distinguish injury risk for this particular population, likely since this population is unaccustomed to performing high velocity change of direction tasks. Further, the repetitive hopping task serves as intermediate task for monitoring athletic populations and thus may not elicit a similar stiffness response represented in sport specific tasks as the performance demands may be lower.

The present study is novel in assessing longitudinal changes and the associated injury risk during sports-specific and dynamic tasks in female populations. However due to the applied nature of the study it was limited by a few factors. Despite the fact that the majority of available high level athletes were recruited, numbers are still relatively limited reducing statistical power. Within the recruited sample there was a high injury incidence which may confound the statistical analysis associated with determining injury risk due to the low number of uninjured athletes. Although the assessment of sports-specific tasks is a strength of the study, this limited testing to isolated time points during each athletic populations' training cycle. As a result, stiffness fluctuations in response to variations in training load and a precise measurement of stiffness immediately prior to and following the injury is somewhat unknown.

8.6 Practical Applications

Chronic athletic training appears to influence longitudinal variations in leg stiffness within athletic populations during sports-specific tasks, which may place them at increased risk of injury. It appears an optimal range of stiffness exists for athletes to allow for optimal performance and minimised injury risk. Furthermore, the training background of athletes appears to influence the appropriateness of tasks in predicting injuries and identifying longitudinal stiffness changes. The results provide practical insight into the importance and need for practitioners, coaches and researchers in utilising sports-specific tasks to assess injury risk and longitudinal stiffness changes in athletes. However, these tasks are potentially impractical monitoring tools as they are currently limited to a laboratory setting. Repetitive hopping may serve as an 'intermediate tool' however care needs to be taken in the interpretation of results. Future research should investigate the potential and validity of sensor technology to quantify stiffness in the daily training environment to allow for ongoing monitoring of athletes during sports-specific tasks and quantification of leg stiffness responses to magnitude changes in training load and associated injury risk.

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Chapter 9. Discussion

9.1 Overview

Athlete screening and monitoring is essential in high performance sport in order to provide relevant information to athletes and coaches on ways to enhance performance and minimise the risk of injury. Identification of appropriate monitoring tools relevant to an athlete's daily training environment is essential to gain an understanding of the contributory mechanisms that may enhance performance output or place athletes at risk of injury. Early detection of potential injury incidence and influence of chronic athletic training on mechanisms which may contribute to injury amongst high level athletes is critical for the implementation of possible prevention strategies in order to reduce training days lost.

Lower-extremity stiffness can quantify the relationship between how athletes modulate force during ground contact, by modelling the lower limb as a simple linear spring allowing for an objective measure of the musculoskeletal response to load (Butler et al., 2003). Additionally, measures of joint stiffness can estimate the stiffness about a joint, providing insight into the control strategies employed by athletes during loading. Research has established that lower-extremity stiffness is linked to athletic performance and potential injury risk (Butler et al., 2003). Athletic training aids in the development of key lower limb and joint stiffness modulation strategies such as the musculoskeletal system, neuromuscular control, co-contraction and regulations of muscle activity (Ambegaonkar et al., 2011a; Kuitunen, Avela, et al., 2002; Kuitunen et al., 2007; Kuitunen et al., 2011). However, profiling the influence of athletic training on lower-extremity stiffness to gain an understanding of appropriate monitoring tools to implement and evaluate control strategies utilised by athletes is unclear. While there are known links between stiffness and performance parameters, there is limited research on the impact of training habits on the longitudinal changes in stiffness in athletes. Thus, there is a need to evaluate longitudinal stiffness changes across a season of training from a performance and injury perspective in high level athletes. Assessment of lower-extremity stiffness and the associated control strategies utilised by athletes from varied training backgrounds has the potential to provide valuable insight into the role athletic training has on lower-extremity stiffness and its association to performance and injury risk.

The present thesis aimed to:

1- Investigate the differences in leg and joint stiffness between athletes from varied training backgrounds during discrete jumping tasks traditionally utilised to assess stiffness. Further, to evaluate the kinematic and kinetic mechanisms athletic populations utilise to modulate stiffness.
2- Investigate differences in leg stiffness and performance variables between athletes from varied training backgrounds during dynamic and sports-specific tasks. Additionally, to evaluate the relationship between stiffness during dynamic jumping and sports-specific tasks.
3- Evaluate differences in leg and joint stiffness in varying female athletic sub-populations and subsequent kinematic and kinetic mechanisms athletic populations utilise to modulate stiffness to meet sports-specific task demands.
4- Assess the longitudinal changes in leg stiffness across a season of training in female athletic sub-populations and the associated injury risk during dynamic and sports-specific tasks.

9.2 Summary of Hypothesis and Findings

9.2.1 Chapter 5- Lower Body Stiffness Modulation Strategies in Well Trained Female Athletes

Hypothesis 1- During discrete jump tasks leg stiffness, joint stiffness and the contributory mechanisms would be different between sub-populations as a result of the varied training and conditioning backgrounds of athletes.

Results partially supported the hypothesis that leg stiffness, joint stiffness and the contributory mechanisms would differ between female sub-populations in discrete jump tasks. No differences in leg stiffness were evident between the investigated sub-populations, despite a range of identified differences in joint contributions and the underlying kinematic movement strategies utilised by groups to modulate leg and joint stiffness to meet varying task demands. It appears basic maximal jumping tasks traditionally implemented to assess stiffness lack the adequate sensitivity to identify stiffness differences between groups with varying habitual training backgrounds. These findings highlight the importance of giving due attention to the selection of appropriate monitoring tasks for the assessment of stiffness within athletic populations from a performance and injury perspective.

9.2.2 Chapter 6- Variations in Lower Body Stiffness During Sports-Specific Tasks in Well Trained Female Athletes

Hypothesis 2- During dynamic reactive jumps tasks and sports-specific tests leg stiffness and its components would differ between sub-populations as a result of varied training and conditioning backgrounds. It was also theorised that dynamic reactive jumping tasks may provide an adequate relationship to sports-specific tests.

Differences in leg stiffness and its components were observed between the investigated groups across all dynamic and sports-specific tasks, supporting the hypothesis that athletes from varied training backgrounds would display differences in leg stiffness and control strategies. Furthermore, it appeared leg stiffness derived from repetitive hopping was moderately related to leg stiffness measures of sports-specific tasks in athletic populations. It was theorised that differences in leg stiffness were due to inherent training variance, subsequently influencing the control strategies utilised by the investigated populations. The training background of athletes influences the relationships between stiffness and performance observed between tasks, highlighting the importance of utilising functional tasks specific to an athlete's habitual training background in athlete screening and monitoring. The results suggest that repetitive hopping may be an intermediate monitoring tool for stiffness assessment in athletic populations since it appears to identify stiffness variations between groups.

9.2.3 Chapter 7- Variations in Lower Body Stiffness Modulation Strategies During Sports-Specific Tasks in Well Trained Female Athletes

Hypothesis 3- Stiffness modulation mechanisms including joint stiffness would vary between the investigated sub-populations during dynamic reactive jump tasks and sports-specific tests as a result of their varied training and conditioning backgrounds.

Results supported the hypothesis that leg stiffness, joint stiffness and the kinematic and kinetic mechanisms athletes utilise to modulate stiffness during sports-specific tasks would differ between the investigated groups. Athletic populations displayed training-specific joint control strategies, where netball athletes utilised key contributions of knee and ankle stiffness, known to be a key contributing joint in enhanced sprinting, change of direction and dynamic jumping performance. In contrast, endurance athletes utilised key contributions of hip stiffness necessary for generating running velocity. Understanding kinematic and kinetic stiffness modulation strategies athletes utilise during sports-specific tasks is of importance to gain further insight into the influence of chronic athletic training on leg and joint stiffness. It appears training influences modulation strategies which are specific to each athletic population as a result of their habitual training background.

9.2.4 Chapter 8- Longitudinal Lower Body Stiffness Variations and Associated Injury Risk During Sports-specific Tasks in Well Trained Female Athletes

Hypothesis 4- Leg stiffness would vary across a season of training and stiffness responses would differ between sub-populations as a result of varied training and conditioning backgrounds. It was also theorised that high levels of stiffness would be linked to overuse injuries and lower levels of stiffness would be associated with soft tissue injuries. Finally, it was hypothesised that injury risk would vary between sub-populations.

The hypothesis that leg stiffness would vary across a season of training and would differ between sub-populations due to varied training and conditioning background of athletes was supported by the results of this study. Further, when compared to generic tasks, sports-specific assessment tasks were superior for identifying stiffness variations and injury risk in athletes. It appeared that an optimal range of stiffness may exist for athletes for optimal performance and minimised injury risk. Additionally, it appears higher level of stiffness may place athletes at high risk of overuse injuries, while lower levels of stiffness appear to be associated with soft tissue injury incidence. The use of sports-specific tasks to predict injuries and identify longitudinal changes in neuromechanical properties appears dependent on the relevance of these tasks to the athlete's habitual training background. This again highlights the importance and need for practitioners, coaches and researchers to utilise sports-specific tasks to assess injury risk and longitudinal changes in stiffness among athletic populations.

9.3 Discussion

Collectively, the results from this series of related studies show that athletic training has a clear influence on lower-extremity stiffness and the associated mechanisms athletes utilise to modulate stiffness. Findings of this body of work considerably strengthen the importance of considering an athlete's habitual training background when assessing stiffness from a performance enhancement and injury prevention perspective. Traditionally, lower limb stiffness has been monitored using discrete jump tasks, however these tasks appear to lack adequate sensitivity to discriminate between groups who differ in stiffness modulation strategies. These findings highlight the importance to coaches and practitioners of utilising sport-specific tasks in athlete screening and monitoring. Although sports-specific tasks serve as a direct reflection of an athlete's typical stiffness characteristics during the daily training environment, these tasks may be impractical in regular monitoring as they are generally isolated to the laboratory setting and require the use of complex motion analysis systems. It would appear that repetitive hopping may serve as a simplistic, intermediate monitoring tool in athletic populations, however appropriate levels of caution is required in the interpretation of findings. It has been suggested that chronic athletic training influences the kinematic and kinetic strategies athletes utilise to modulate stiffness. The findings of this thesis supports this notion, where it was clear that athletes employ population specific joint control strategies to modulate stiffness reflective of the demands of the athletic training background.

Chronic athletic training influences changes in longitudinal stiffness across a season of training thereby allowing athletes to meet performance demands, however this may place athletes at an increased risk of injury. Firstly, the findings provide evidence of normative pre, post and off season stiffness data for high level netball and endurance athletic populations. Additionally, the results establish how stiffness shifts through a seasonal of chronic athletic training, which has previously been unknown. In line with previous research, lower levels of stiffness appear to place athletes at an elevated risk of soft tissue injury, while higher levels of stiffness are linked to overuse injuries (Butler et al., 2003). Outcomes suggest there may be an optimal range of leg stiffness for enhanced athletic performance and minimised injury risk, with further research required to examine the determination of this range in more detail. It would appear that leg stiffness elicited during tasks specific to an athlete's training background are an adequate monitoring tool for identifying potential injury risk amongst athletes. While the repetitive hopping task did not provide the same, significant, lower-extremity stiffness seasonal fluctuation as sports-specific tasks, it did display similar seasonal stiffness patterns. Repetitive hopping appears to be an intermediate longitudinal monitoring tool, however, given its potential limitations, care needs to be taken in the interpretation of results and findings. Although the exact mechanism that leads to increased injury risk, such as magnitude changes in load and stiffness adjustments at the joint level remain unknown, this body of work has established that it is possible to monitor neuromechanical properties as a tool to identify athletes at risk of injury.

9.3.1 Strengths

The present thesis endeavoured to investigate the influence of stiffness in high level athletic populations from different sports and training backgrounds. A number of strengths of the research design, implementation and findings are suggested:

- The variety of tasks included in the testing battery, from discrete basic jumping tasks traditionally utilised to assess stiffness, to sports-specific tasks, enabled an increased understanding as to the relevance of these tasks in athlete screening along with their application to an applied sporting realm.

- The inclusion of sports-specific tasks provided functional relevance to athletic populations. This further extends the knowledge and evidence regarding applied stiffness measures and the associated longitudinal stiffness changes in response to training demands during tasks where stiffness properties may have a closer reflection of training and competition demands.

- Previous research has typically assessed lower-extremity stiffness in recreationally active males or athletic populations involved in power/sprinting activities. The inclusion of different female athletic populations allows for comparisons across a spectrum of varying habitual training backgrounds and sports-specific tasks. Furthermore, this provided different insights into how athletes from varied training backgrounds modulate leg stiffness to meet task demands and the role lower-extremity stiffness plays in athletic performance and injury risk.

- Particular focus on female athletes extends the limited stiffness research into this gender. This is a particularly important aspect of this research as this population is known to be at an increased risk of injury incidence when compared to their male counterparts.

- The inclusion of joint stiffness measures and the assessment of the underlying mechanisms which contribute to lower-extremity stiffness modulation provided further insight into the influence of athletic training of lower-extremity stiffness. Additionally, it also enhanced the understanding regarding the stiffness modulation strategies utilised by various athletic populations to the meet the performance demands of tasks.

- The ability to statistically control for variations in running speed and jump frequency, enabled participants to self-select a running speed which was reflective of their competition plan and preferred jump frequency. Subsequently, leg stiffness characteristics, joint stiffness properties and the contributory mechanisms may be more representative of characteristics expressed in the daily training environment.

- The longitudinal assessment of changes in leg stiffness across a season of training at specific training phases provided insight into the influence of chronic athletic training on lower-extremity stiffness.

- The prospective approach to the prediction of injury risk during sports-specific tasks in relation to lower-extremity stiffness provided improved understanding and support for the links between leg stiffness, athletic performance and injury risk.

- The advancement in knowledge pertaining to potential injury risk factors resulting from chronic athletic training and the possibility of identifying at risk athletes is of critical importance in high performance sport. The ability to identify relevant tasks for injury prediction of athletic populations and the associated leg stiffness risk factors is relevant for future injury identification and prevention strategies for practitioners, coaches and athletes in high performance sport.

9.3.2 Limitations

The present thesis aimed to investigate the influence of high level athletic training on stiffness in athletes from varied habitual training backgrounds. Due to the applied nature of the research design, certain limitations were evident which influence the application of the findings; these include:

- Participants of the athletic sub-populations were recruited at a relatively high level of competition. Variability in the training hours, load, intensity and competition priorities between participants may have influenced lower-extremity stiffness changes and associated injury risk, however these factors were beyond the control of researchers.

- A sufficient sample size from a pure power athletic group such as sprinters or jumpers was unable to be recruited, potentially limiting comparisons between this research and previous research. Furthermore, it may have limited the understanding into the influence of athletic training on lower-extremity stiffness and the relevance of results to a wider range of sporting populations.

- Despite the best efforts of researchers to obtain complete weekly training diaries in order to determine training load of participants, there was poor compliance. As a result, full data sets were unable to be achieved and training hours were utilised as a training load measure. This may have limited the understanding of lower-extremity stiffness changes in response to training load, which may ultimately have influenced the results.

- While the longitudinal design was a strength of this research, retention of participants was challenging. Although the researchers endeavoured to recruit a suitable sample size, participant dropout did occur due to injury and athlete relocation, subsequently reducing participant numbers and statistical power, particularly for injury analysis.

- Although the assessment of sports-specific tasks enhances the application and relevance of results to sporting populations, it is limited to a laboratory setting due to the need for 3D motion analysis. This reduced the opportunity for regular monitoring and therefore may have limited/narrowed the ability to directly assess stiffness changes in response to load, performance and prior to and following injury incidence.

- Questions around the reliability of joint stiffness measures excluded these measures from longitudinal analysis. It was unknown if variance occurred in measures as a result of inherent individual variability. Subsequently, it remains unknown whether the underlying contributory mechanisms for the observed changes in leg stiffness occurred as a result of neuromuscular adjustment or occurrence of injury.

9.3.3 Practical Recommendations and Future Direction

The present thesis identified that chronic athletic training has a strong influence on leg stiffness, joint stiffness and contributory kinematic mechanisms which modulate stiffness. Additionally, it was clear stiffness was associated with injury incidence and was a key identifier in injury prediction in athletes. A number of recommendations and suggestions for future research emanate from the findings of this thesis:

- Discrete maximal effort jumping tasks traditionally used to assess and monitor stiffness appear to lack adequate sensitivity to identify modulation differences between athletic groups from varied training backgrounds. This questions the appropriateness of these tasks to monitor and assess stiffness athletic cohorts. If screening tools do not represent an athlete's typical leg stiffness and joint modulation strategies during training and competition, this may potentially mask any evident relationship to injury risk or performance.

- It may be more beneficial to screen athletes with dynamic and functional tasks relevant to their habitual training background reflective of training and competition demands. It would appear athletes optimise stiffness differently to meet performance demands due to inherent training variance and subsequent control strategies. Accordingly, practitioners monitoring lower-extremity stiffness and assessing longitudinal differences from a performance capacity or injury risk perspective should consider utilising tasks relevant to athletic populations.

- Regular monitoring of lower-extremity stiffness may provide useful insight into potential training adaptations in high impact athletes and the potential influence of these training interventions. Although sports-specific tasks serve as a direct reflection of stiffness during training and competition, these tasks are potentially impractical monitoring tools as they require the use of motion analysis and are limited to a laboratory stetting. Repetitive hopping may provide a suitable simple 'intermediate' monitoring tool to assess an athlete's stiffness during daily training, however care needs to be taken by practitioners in the interpretation of results particularly from an injury perspective.

- Kinematic and kinetic modulation strategies that athletic populations utilise to meet training and competition demands may be a contributory factor in specific predispositions to particular injuries within athletic populations.

- Pre-season screening of netball and endurance track and field athletes using similar leg stiffness measures and protocols for sports-specific tasks may assist practitioners in identifying athletes at risk of lower limb injury. Monitoring of training load and potential symptoms of athletes identified at risk may assist in early detection and possible injury prevention.

- An optimal band range of leg stiffness appears to exist for athletic populations which allows for optimal performance and minimised injury risk. However, this notion requires further investigation to explore how this optimal band range may shift with magnitude changes in training load and intensity and the specific range for individual athletic populations.

- Applied injury research aims to convert injury risk assessment into injury prevention in athletes. Investigation into the ability of emerging sensor technology, such as inertial measurement units, to quantify stiffness in the daily training environment may further enhance the understanding of the relationships between lower-extremity stiffness and mechanical load in performance enhancement and injury incidence. Utilising technology that has the ability to regularly monitor leg stiffness in response to magnitude changes in load and intensity during training and competition may have the potential to reduce the incidence of injury amongst a critical populations where reducing training days lost is of the utmost importance.

- Prospective studies involving a larger cohort of athletes from a wider range of sports during sports-specific tasks would strengthen the evidence and extend the knowledge as to the influence of training on lower-extremity stiffness and its ability to predict lower limb injury incidence. Further prospective research should investigate the underlying joint mechanisms which contribute to lower-extremity stiffness modulation that athletes use. This may enhance understanding as to why athletes may be at risk of injury and the influence of chronic athletic training on stiffness.

9.4 Conclusion

Understanding the influence of athletic training on lower-extremity stiffness and the associated contributory mechanisms is important to enhance performance and minimise injury risk in high performance sport. Lower-extremity stiffness plays a critical role in monitoring performance and injury risk in high level athletes from high impact sports. There is a need to identify appropriate monitoring tools that reflect an athlete's typical stiffness characteristics during training and competition and to gain an understanding of the mechanisms which contribute to stiffness modulation strategies. Furthermore, it is important to gain insight into the longitudinal changes in lower-extremity stiffness across a training cycle and the ability of tasks to identify 'at risk' athletes as this may aid in improving injury prevention amongst athletic populations.

Athlete screening and monitoring is important in high performance sport in order to provide relevant information to coaches and athletes on ways to optimise performance and minimise injury risk. Although researchers and practitioners have traditionally utilised discrete jumping tasks to monitor stiffness, these tasks appear to lack adequate sensitivity to discriminate lower-extremity stiffness differences between varying athletic groups, despite clear differences at the joint level. Accordingly, there is a need for practitioners, coaches and athletes to consider an athlete's habitual training background when identifying tasks to monitor lower limb stiffness. It would appear that dynamic and sports-specific tasks are more relevant screening tools in athletic populations as opposed to traditional discrete jumping tasks.

Chronic athletic training has a clear influence on the modulation strategies athletes utilise to adjust stiffness to meet tasks demands. Understanding the lower-extremity stiffness modulation strategies athletes utilise may provide insight into the mechanisms which may place athletes at risk of injury; however this notion requires further investigation. Lower-extremity stiffness measures during sports-specific tasks relevant to an athlete's habitual training background appear suitable for identifying athletes at increased risk of injury. Furthermore, it would appear an optimal range of stiffness may exist for athletic populations for minimised risk of injury, as extreme high or low levels of stiffness appear to place athletes at an elevated risk of overuse and soft tissue injuries respectively. The incorporation of appropriate screening tools may assist coaches and practitioners in early detection of at risk athletes. This may allow for further investigation into the additional risk factors which may predispose athletes to injury risk, including magnitude changes in training load and potential contributory kinematic mechanisms. Although additional research is needed, this body of work contributes to advancements in screening and monitoring of high level athletes, with a wide variety of applications for a multitude of practitioners.

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APPENDICES

APPENDIX A – STROBE CRITERIA

STROBE Statement—checklist of items that should be included in reports of observational studies

	Item No	Recommendation
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found
Introduction		
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported
Objectives	3	State specific objectives, including any prespecified hypotheses
Methods		
Study design	4	Present key elements of study design early in the paper
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group
Bias	9	Describe any efforts to address potential sources of bias
Study size	10	Explain how the study size was arrived at
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding
		(*b*) Describe any methods used to examine subgroups and interactions
		(*c*) Explain how missing data were addressed
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy
		(*e*) Describe any sensitivity analyses

Results		
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed
		(b) Give reasons for non-participation at each stage
		(c) Consider use of a flow diagram
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders
		(b) Indicate number of participants with missing data for each variable of interest
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time
		Case-control study—Report numbers in each exposure category, or summary measures of exposure
		Cross-sectional study—Report numbers of outcome events or summary measures
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included
		(*b*) Report category boundaries when continuous variables were categorized
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses
Discussion		
Key results	18	Summarise key results with reference to study objectives
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence
Generalisability	21	Discuss the generalisability (external validity) of the study results
Other information		
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

APPENDIX B – PRISMA CHECKLIST

Section/topic	#	Checklist item	Reported on page #
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	50
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	N/A
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	50-53
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	53
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	54-55
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	56
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	53-57
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	54-55
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	56-57
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	57

Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	58
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	58
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	N/A
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	N/A
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	N/A
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	57
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	57-88
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	86-87
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	57-88
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	N/A
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	N/A
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	N/A
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	89-97
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	97-98

Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	99
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	N/A

From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(6): e1000097. doi:10.1371/journal.pmed1000097

Note- N/A not applicable to this systematic review

APPENDIX C – ETHICAL APPROVAL

ACU
AUSTRALIAN CATHOLIC UNIVERSITY

Human Research Ethics Committee
Committee Approval Form

Principal Investigator/Supervisor: Raul Landeo Melbourne Campus

Co-Investigators: Melbourne Campus

Student Researcher: Emma Millett Melbourne Campus

Ethics approval has been granted for the following project:
Influence of Athletic Training on Stiffness Attenuation

for the period: 9/12/2011-15/08/2013

Human Research Ethics Committee (HREC) Register Number: N2011 65

Special Condition/s of Approval
Prior to commencement of your research, the following permissions are required to be submitted to the ACU HREC:

The following standard conditions as stipulated in the *National Statement on Ethical Conduct in Research Involving Humans* (2007) apply:

(i) that Principal Investigators / Supervisors provide, on the form supplied by the Human Research Ethics Committee, annual reports on matters such as:
- security of records
- compliance with approved consent procedures and documentation
- compliance with special conditions, and

(ii) that researchers report to the HREC immediately any matter that might affect the ethical acceptability of the protocol, such as:
- proposed changes to the protocol
- unforeseen circumstances or events
- adverse effects on participants

The HREC will conduct an audit each year of all projects deemed to be of more than low risk. There will also be random audits of a sample of projects considered to be of negligible risk and low risk on all campuses each year.

Within one month of the conclusion of the project, researchers are required to complete a *Final Report Form* and submit it to the local Research Services Officer.

If the project continues for more than one year, researchers are required to complete an *Annual Progress Report Form* and submit it to the local Research Services Officer within one month of the anniversary date of the ethics approval.

Signed: .... Date: ....09/12/2011............
(Research Services Officer, Melbourne Campus)

APPENDIX D – PARTICIPANT INFORMATION LETTER AND CONSENT FORM

AUSTRALIAN CATHOLIC UNIVERSITY

INFORMATION LETTER TO PARTICIPANTS

INFLUENCE OF ATHLETIC TRAINING ON STIFFNESS

Ms Emma Millett (PhD Student Researcher)
Dr David Greene (Principal Supervisor)
Dr Mark Moresi (Co-Supervisor)

Doctor of Philosophy

Location: Biomechanics laboratory (STR/Biomechanics Lab), Mount Saint Mary
25A Barker Road Strathfield NSW 2135

Dear Participant,

You are invited to participate in the above study, which is conducted in order to meet the requirements for a doctorate degree. The purpose of the study is to profile the influence of various athletic training types on muscle stiffness, a measure of your "springy-ness", commonly used as a gauge of performance and injury risk. This will allow the opportunity to gain an understanding of any stiffness changes to athletic demographics, potential performance benefits and muscle adaptations during a 10 month period. In addition, we will be able to provide you with a biomechanical profile of leg stiffness relative to training specific tasks.

The study will involve analysis of your lower limb and joint movements, force production and muscle activation during a jump sequence. To do this will require you, the participant, to perform jump sequences in front of a motion capture system. This will require small reflective markers to be attached to your skin identifying various anatomical landmarks on your body. Also surface electrodes for muscle activation collection will be attached on the lower limb. These measures and tasks are low risk to you as a participant and do not involve any invasive procedures. The electrodes and markers used are attached via hypoallergenic adhesive tape to the skin at standard sites on the limbs being observed. Removal is quick and easy and will cause very low to no discomfort. At times it may be required to shave small areas of the skin in order to ensure proper adhesion of these attachments. This will also reduce any discomfort when maker/electrode is removed. If shaving is required it will be carried out using single use disposable razors following an alcohol swab. Non latex rubber gloves will also be worn and/or made available to you. You will have the choice whether to perform the shaving yourself or have an experienced member of the research team carry it out.

You will be asked to perform five trials of each of six (6) standard vertical and horizontal maximal and repetitive jump tasks, such as hopping, sprinting and bouncing. These tasks will be both maximal effort and sub-maximal effort in nature. Testing is no more risky or rigorous than what you would normally undertake in training or competition. You will be asked to attend three testing sessions and fill out standardised questionnaires and training diaries over a period of ten months. The testing sessions will occur over the course of your regular training cycle during pre, post and off season. These specific phases have been identified in order to ensure testing does not interfere with your designated training cycle, while allowing for training influences to be tracked. You will also be asked to provide certain body measures including height and weight. Each session should last no longer than one and half hours and will be conducted in the biomechanics laboratory at the Australian Catholic University, Strathfield campus,on a mutually agreed upon time and date.

In order to participate in the study it is required that you are currently free of injury, compete in maximal (e.g. sprinting), high-intensity team sport (e.g. basketball, netball etc.) or endurance (e.g. middle/long distance track, cross country, triathlon etc.) disciplines or are a healthy sedentary individual. A performance criterion has also been set so that participants included in the study are of a similar skill level. As a participant in the research study you have the right to refuse your consent to participate at any time. You are not obligated to notify the researchers of any reasoning for your discontinuation in the study. Neither your coach nor anyone else involved in training and/or team selection etc. will be notified of your withdrawal from the project if you choose to do so. Any information you provide will be treated with the utmost confidentiality. Any reported data will be group data. No individual identifying characteristics attached to any data will exist. Data for this study will be stored in a secure location accessible only to the researchers and will not be passed on to any third party.

Any questions you may have regarding this research study should be directed to the Principal Investigator (or Supervisor) and the Student Researcher:

Principal Supervisor

David Greene

David.Greene@acu.edu.au
Exercise Science
Strathfield Campus (Mount St Mary)
25A Barker Road Strathfield NSW 2135
Locked Bag 2002 Strathfield NSW 2135

PhD Student Researcher

Emma Millett
0407 410 832
s00068263@myacu.edu.au or
Emma.Millett@nswis.com.au
Exercise Science
25A Barker Road Strathfield NSW 2135
Locked Bag 2002 Strathfield NSW 2135

Upon completion the research team will honour you request for feedback as to study results and findings. Please don't hesitate to call or email (details above) if you would like to be provided with an executive summary of results.

This study has been approved by the Human Research Ethics Committee at Australian Catholic University.

In the event that you have an complaint or concern about that way you have been treated during the study, or if you have any queries that the Investigator or Supervisor and Student Researchers has (have) not been able to satisfy, you may write to the Chair of the Human Research Ethics Committee care of the nearest branch of the Research Services Office.

NSW and ACT: Chair, HREC
C/- Research Services
Australian Catholic University
North Sydney Campus
PO Box 968
NORTH SYDNEY NSW 2059
Tel: 02 9739 2105
Fax: 02 9739 2870

Any complaints or concern will be treated in confidence, fully investigated and you will be informed of the outcome.

If you agree to participate in this project, you should sign both copies of the Consent Form, retain one copy for your records and return the other copy to the Supervisor and Student Researcher with your name and number/email so we can organise a session convenient to you.

Regards,

David Greene Emma Millett

AUSTRALIAN CATHOLIC UNIVERSITY

CONSENT FORM

Copy for Participant to Keep

INFLUENCE OF ATHLETIC TRAINING ON STIFFNESS

Ms Emma Millett (PhD Student Researcher)
Dr David Greene (Principal Supervisor)
Dr Mark Moresi (Co-Supervisor)
Doctor of Philosophy

Location: Biomechanics laboratory (STR/Biomechanics Lab), Mount Saint Mary

I .... *(The participant)* have read *(or, where appropriate, have had read to me)* and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction. I agree to participate in the three one and half hour testing sessions of lower-extremity stiffness production under fatigued conditions and the use of motion analysis cameras, force plate and electromyography to capture information about my movement on a mutually agreed upon time and date. I agree to partake in questionnaires and training diaries. I do so realising that I can withdraw my consent at any time without adverse consequence. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way.

NAME OF PARTICIPANT: ....

CONTACT NUMBER: ....

CONTACT EMAIL: ....

SIGNATURE .... DATE ....

SIGNATURE OF SUPERVISOR:..

DATE:............................

SIGNATURE OF STUDENT RESEARCHER: ....

DATE:................................

AUSTRALIAN CATHOLIC UNIVERSITY

CONSENT FORM

Copy for Researcher to Keep

INFLUENCE OF ATHLETIC TRAINING ON STIFFNESS

Ms Emma Millett (PhD Student Researcher)
Dr David Greene (Principal Supervisor)
Dr Mark Moresi (Co-Supervisor)
Doctor of Philosophy

Location: Biomechanics laboratory (STR/Biomechanics Lab), Mount Saint Mary

I ………………………………………….. *(The participant)* have read *(or, where appropriate, have had read to me)* and understood the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction. I agree to participate in the three one and half hour testing session of lower-extremity stiffness production under fatigued conditions and the use of motion analysis cameras, force plate and electromyography to capture information about my movement on a mutually agreed upon time and date. I agree to partake in questionnaires and training diaries. I do so realising that I can withdraw my consent at any time without adverse consequence. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify me in any way.

NAME OF PARTICIPANT: ……………………………………………………………………………………………

CONTACT NUMBER: ……………………………………………………………………………………………

CONTACT EMAIL: ……………………………………………………………………………………………

SIGNATURE …………………………………………………. DATE ……………………………

SIGNATURE OF SUPERVISOR: ……………………………………………………………………………………

DATE:……………………….

SIGNATURE OF STUDENT RESEARCHER: …………………………………………………………………

DATE:…………………………….

APPENDIX E – PARENTAL INFORMATION LETTER AND ASCENT FORM

ACU
AUSTRALIAN CATHOLIC UNIVERSITY

INFORMATION LETTER TO PARENTS/GUARDIAN

INFLUENCE OF ATHLETIC TRAINING ON STIFFNESS

Ms Emma Millett (PhD Student Researcher)
Dr David Greene (Principal Supervisor)
Dr Mark Moresi (Co-Supervisor)
Doctor of Philosophy

Location: Biomechanics laboratory (STR/Biomechanics Lab), Mount Saint Mary
25A Barker Road Strathfield NSW 2135

Dear Parent or Guardian,

Your child is invited to participate in the above study, which is conducted in order to meet the requirements for a doctorate degree. The purpose of the study is to profile the influence of various athletic training types on muscle stiffness, a measure of your "springy-ness", commonly used as a gauge of performance and injury risk. This will allow the opportunity to gain an understanding of any stiffness changes to athletic demographics, potential performance benefits and muscle adaptations during a 10 month period. In addition, we will be able to provide you and your child with a biomechanical profile of leg stiffness relative to training specific tasks.

The study will involve analysis of lower limb and joint movements, force production and muscle activation during a jump sequence. To do this will require your child to perform jump sequences in front of a motion capture system. This will require small reflective markers attached to your child's skin identifying various anatomical landmarks on their body. In addition, small surface electrodes for muscle activation collection will be attached on the lower limb. These measures and tasks are low risk to you as a participant and do not involve any invasive procedures. The electrodes and markers used are attached via hypoallergenic adhesive tape to the skin at standard sites on the limbs being observed. Removal is quick and easy and will cause very low to no discomfort. At times it may be required to shave small areas of the skin in order to ensure proper adhesion of these attachments. This will also reduce any discomfort when maker/electrode is removed. If shaving is required it will be carried out using single use disposable razors following an alcohol swab. Non latex rubber gloves will also be worn and/or made available to you and/or your child. You and your child will have the choice whether to perform the shaving yourself or have an experienced member of the research team carry it out.

Your child will be asked to perform five trials of each of six (6) standard vertical and horizontal maximal and repetitive jump tasks, such as hopping and bouncing. These tasks will be both maximal effort and sub-maximal effort in nature. Testing is no more risky or rigorous than what your child would normally undertake in training or competition. Your child will be asked to attend three testing sessions and fill out standardised questionnaires and training diaries over a period of ten months. The testing sessions will occur over the course of your child's regular training cycles during pre, post and off season. These specific phases have been identified in order to ensure testing does not interfere with their designated training cycle, while allowing for training influences to be tracked. Your child will also be asked to provide certain body measures including height and weight. Each session should last no longer than one and half hours and will be conducted in the biomechanics laboratory at the Australian Catholic University, Strathfield campus, on a mutually agreed upon time and date.

In order to participate in the study it is required that your child is currently free of injury, competes in maximal (e.g. sprinting), high-intensity team sport (e.g. basketball, netball etc.) or endurance (e.g. middle/long distance track, cross country, triathlon etc.) disciplines or are healthy sedentary individual. A performance criterion has also been set so that participants included in the study are of a similar skill level. As a parent/guardian of a participant in the research study you and your child have the right to refuse your consent to participate at any time. You are not obligated to notify the researchers of any reasoning for your discontinuation in the study. Neither your coach nor anyone else involved in training and/or team selection etc. will be notified of your withdrawal from the project if you choose to do so. Any information you provide will be treated with the utmost confidentiality. Any reported data will be group data. No individual identifying characteristics attached to any data will exist. Data for this study will be stored in a secure location accessible only to the researchers and will not be passed on to any third party.

Any questions you may have regarding this research study should be directed to the Principal Investigator (or Supervisor) and the Student Researcher:

Principal Supervisor

David Greene

David.Greene@acu.edu.au
Exercise Science
Strathfield Campus (Mount St Mary)
25A Barker Road Strathfield NSW 2135
Locked Bag 2002 Strathfield NSW 2135

Student Researcher

Emma Millett
0407 410 832
s00068263@myacu.edu.au or
Emma.Millett@nswis.com.au
Exercise Science
25A Barker Road Strathfield NSW 2135
Locked Bag 2002 Strathfield NSW 2135

Upon completion the research team will honour your request for feedback as to study results and findings. Please don't hesitate to call or email (details above) if you would like to be provided with an executive summary of results.

This study has been approved by the Human Research Ethics Committee at Australian Catholic University.

In the event that you have an complaint or concern about that way you or your child has been treated during the study, or if you have any queries that the Investigator or Supervisor and Student Researchers has (have) not been able to satisfy, you may write to the Chair of the Human Research Ethics Committee care of the nearest branch of the Research Services Office.

NSW and ACT: Chair, HREC
C/- Research Services
Australian Catholic University
North Sydney Campus
PO Box 968
NORTH SYDNEY NSW 2059
Tel: 02 9739 2105
Fax: 02 9739 2870

Any complaints or concern will be treated in confidence, fully investigated and you will be informed of the outcome.

If you agree for your child to participate in this project, you should sign both copies of the Consent Form, retain one copy for your records and return the other copy to the Supervisor and Student Researcher with your name and number/email so we can organise a session convenient to you.

Regards,

David Greene   Emma Millett

AUSTRALIAN CATHOLIC UNIVERSITY

CONSENT/ASCENT FORM

Copy for Parent to Keep

INFLUENCE OF ATHLETIC TRAINING ON STIFFNESS

Ms Emma Millett (PhD Student Researcher)
Dr David Greene (Principal Supervisor)
Dr Mark Moresi (Co-Supervisor)
Doctor of Philosophy

Location: Biomechanics laboratory (STR/Biomechanics Lab), Mount Saint Mary

I .... *(The parent/guardian)* have read *(or, where appropriate, have had read to me)* and understood the information provided in the Letter to Parents. Any questions I have asked have been answered to my satisfaction. I agree for my child, nominated below, to participate in the three one and half hour testing sessions of lower-extremity stiffness production under fatigued conditions and the use of motion analysis cameras, force plate and electromyography to capture information about my child's movement on a mutually agreed upon time and date. I agree for my child to partake in questionnaires and training diaries. I do so realizing that I can withdraw my consent at any time without adverse consequence. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify my child in any way.

NAME OF PARENT/GUARDIAN: ....

CONTACT NUMBER: ....
CONTACT EMAIL: ....

SIGNATURE .... DATE ....

NAME OF CHILD: ....

SIGNATURE OF SUPERVISOR:...

DATE:...........................

SIGNATURE OF STUDENT RESEARCHER: ....

DATE:................................

ASCENT OF PARTICIPANTS AGED UNDER 18 YEARS

I ………………………………………….. *(The participant aged under 18 years)* understand what this research project is designed to explore. What I will be asked to do has been explained to me. I agree to participate in the one and half hour testing sessions of lower-extremity stiffness production under fatigued conditions and the use of motion analysis cameras, force plate and electromyography capture information about my movement on a mutually agreed upon time and date. I agree to partake in questionnaires and training diaries. I do so realising that I can withdraw my consent at any time without adverse consequences.

NAME OF PARTICIPANT AGED UNDER 18: ………………………………………………………………………………

SIGNATURE ………………………………………………….. DATE …………………………..

SIGNATURE OF SUPERVISOR: ……………………………………………………………………………………………

DATE:……………………….

SIGNATURE OF STUDENT RESEARCHER: ………………………………………………………………………………

DATE:…………………………..

AUSTRALIAN CATHOLIC UNIVERSITY

PARENT/GUARDIAN CONSENT FORM

Copy for Researcher to Keep

INFLUENCE OF ATHLETIC TRAINING ON STIFFNESS

Ms Emma Millett (PhD Student Researcher)
Dr Raul Landeo (Principal Supervisor)
Dr Mark Moresi (Co-Supervisor)
Doctor of Philosophy

Location: Biomechanics laboratory (STR/Biomechanics Lab), Mount Saint Mary

I ……………………………………………. *(The parent/guardian)* have read *(or, where appropriate, have had read to me)* and understood the information provided in the Letter to Parents. Any questions I have asked have been answered to my satisfaction. I agree for my child, nominated below, to participate in the three one and half hour testing sessions of lower-extremity stiffness production under fatigued conditions and the use of motion analysis cameras, force plate and electromyography to capture information about my child's movement on a mutually agreed upon time and date. I agree for my child to partake in questionnaires and training diaries. I do so realizing that I can withdraw my consent at any time without adverse consequence. I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify my child in any way.

NAME OF PARENT/GUARDIAN: ………………………………………………………………………………………

CONTACT NUMBER: ……………………………………………………………………………………………
CONTACT EMAIL: ……………………………………………………………………………………………

SIGNATURE ………………………………………………… DATE ……………………………

NAME OF CHILD: ……………………………………………………………………………………………

SIGNATURE OF SUPERVISOR: ………………………………………………………………………………

DATE: ……………………….

SIGNATURE OF STUDENT RESEARCHER: ……………………………………………………………………

DATE: ……………………………

ASCENT OF PARTICIPANTS AGED UNDER 18 YEARS

I ………………………………………….. *(The participant aged under 18 years)* understand what this research project is designed to explore. What I will be asked to do has been explained to me. I agree to participate in the one and half hour testing sessions of lower-extremity stiffness production under fatigued conditions and the use of motion analysis cameras, force plate and electromyography capture information about my movement on a mutually agreed upon time and date. I agree to partake in questionnaires and training diaries. I do so realising that I can withdraw my consent at any time without adverse consequences.

NAME OF PARTICIPANT AGED UNDER 18: ………………………………………………………………………………

SIGNATURE …………………………………………………. DATE …………………………..

SIGNATURE OF SUPERVISOR: ………………………………………………………………………………………

DATE:……………………….

SIGNATURE OF STUDENT RESEARCHER: ……………………………………………………………………………

DATE:…………………………..

APPENDIX F – SCREENING QUESTIONNARIES

AUSTRALIAN CATHOLIC UNIVERSITY

SCREENING FORM (Pre Season)

INFLUENCE OF ATHLETIC TRAINING ON STIFFNESS

Dr David Greene (Principal Supervisor)
Dr Mark Moresi (Co-Supervisor)
Ms Emma Millett (Student Researcher)
Doctoral of Philosophy

Name: ....

Date of Birth: .... Age: ....

Height: ....

Weight: ....

Left Leg Length: ....

Left Knee Width: ....

Left Ankle Width: ....

Left Shoulder Offset: ....

Left Elbow Width: ....

Left Wrist Width: ....

Left Hand Thickness: ....

Right Leg Length: ....

Right Knee Width: ....

Right Ankle Width: ....

Right Shoulder Offset: ....

Right Elbow Width: ....

Right Wrist Width: ....

Right Hand Thickness: ....

Leg Dominance: ………………… ………………… …………………

Average: …………………

Exercise History:

Athletic Background: ……………………………………………………………………………

Athletic Classification:

Endurance   High-intensity Intermittent   Maximal   Recreational

Highest Athletic Level: ……………………………………………………………………………

Training Years: ……………………………………………………………………………

Average Training Hours Pre Week: …………………………………………………………

How Often Pre Week: ……………………………………………………………………………

Typical Training Week: ……………………………………………………………………………

……………………………………………………………………………

……………………………………………………………………………

……………………………………………………………………………

Predominately What Type of Exercise: …………………………………………………………

Sports Injury Details:

Please List Any Current or Recurring Injuries: ………………………………………………

……………………………………………………………………………

……………………………………………………………………………

……………………………………………………………………………

Please List Any Pervious Injuries. When and How They Occurred:

……………………………………………………………………………

……………………………………………………………………………

……………………………………………………………………………

……………………………………………………………………………

……………………………………………………………………………

Do You Suffering Recurring Pain In Any Joint When Participating In Sport:

Yes No

Do You Require Specific Taping/Padding For a Pervious Injury:

Yes No

If Yes Please Detail: ……………………………………………………………………………………

Women's Health History:

Age at Beginning of Menstruation (Periods): …………………………………………………

Average Cycle Length: ……………………………………………………………………………………

AUSTRALIAN CATHOLIC UNIVERSITY

SCREENING FORM (Post Season)

INFLUENCE OF ATHLETIC TRAINING ON STIFFNESS

Dr David Greene (Principal Supervisor)
Dr Mark Moresi (Co-Supervisor)
Ms Emma Millett (Student Researcher)
Doctoral of Philosophy

Name: ....

Date of Birth: .... Age: ....

Height: ....

Weight: ....

Left Leg Length: ....

Left Knee Width: ....

Left Ankle Width: ....

Left Shoulder Offset: ....

Left Elbow Width: ....

Left Wrist Width: ....

Left Hand Thickness: ....

Right Leg Length: ....

Right Knee Width: ....

Right Ankle Width: ....

Right Shoulder Offset: ....

Right Elbow Width: ....

Right Wrist Width: ....

Right Hand Thickness: ....

Exercise History:

Average Training Hours Pre Week: ……………………………………………………………………

How Often Pre Week: ……………………………………………………………………………………

Typical Training Week: ……………………………………………………………………………………

……………………………………………………………………………………

……………………………………………………………………………………

……………………………………………………………………………………

Sports Injury Details:

Please Fill out Injury Report Form If You Have Incurred an Injury in the Last 6 months

Please List Any Current or Recurring Injuries: …………………………………………………………

……………………………………………………………………………………

……………………………………………………………………………………

……………………………………………………………………………………

Do You Suffering Recurring Pain In Any Joint When Participating In Sport:

Yes No

Do You Require Specific Taping/Padding For a Pervious Injury:

Yes No

If Yes Please Detail: ……………………………………………………………………………………

AUSTRALIAN CATHOLIC UNIVERSITY

SCREENING FORM (Off Season)

INFLUENCE OF ATHLETIC TRAINING ON STIFFNESS

Dr David Greene (Principal Supervisor)
Dr Mark Moresi (Co-Supervisor)
Ms Emma Millett (Student Researcher)
Doctoral of Philosophy

Name: ………………………………………………………………………………………

Date of Birth: ……………………………………………… Age: ……………………

Height: ……………………

Weight: ……………………

Left Leg Length: ……………………

Left Knee Width: ……………………

Left Ankle Width: ……………………

Left Shoulder Offset: ……………………

Left Elbow Width: ……………………

Left Wrist Width: ……………………

Left Hand Thickness: ……………………

Right Leg Length: ……………………

Right Knee Width: ……………………

Right Ankle Width: ……………………

Right Shoulder Offset: ……………………

Right Elbow Width: ……………………

Right Wrist Width: ……………………

Right Hand Thickness: ……………………

Exercise History:

Average Training Hours Pre Week: ………………………………………………………………

How Often Pre Week: ………………………………………………………………………………

Typical Training Week: ………………………………………………………………………………

………………………………………………………………………………

………………………………………………………………………………

………………………………………………………………………………

Sports Injury Details:

Please Fill out Injury Report Form If You Have Incurred an Injury in the Last 6 months

Please List Any Current or Recurring Injuries: ……………………………………………………

………………………………………………………………………………

………………………………………………………………………………

………………………………………………………………………………

Do You Suffering Recurring Pain In Any Joint When Participating In Sport:

Yes No

Do You Require Specific Taping/Padding For a Pervious Injury:

Yes No

If Yes Please Detail: ………………………………………………………………………………

APPENDIX G – ONLINE TRAINING DIARY

Training Diary

Please fill out the following information on a weekly basis starting on a Monday.

Information includes type of training session undertaken, duration and rate of percieved exertion. If you undertake two sessions in one day, please record these sessions individually. The perceived rate of exertion (RPE) is the global representation of the entire intensity of the training session. The rating is based on a scale of one to ten.

Rating	Descriptor
0	Rest
1	Very, Very Easy
2	Easy
3	Moderate
4	Somewhat Hard
5	Hard
6	-
7	Very Hard
8	-
9	-
10	Maximal

*Required

Name *

Week (Date starting Monday) *

Day

Please provide brief session details

Duration of session

Rate of Percieved Exertion

	1	2	3	4	5	6	7	8	9	10	
Rest	○	○	○	○	○	○	○	○	○	○	Maximal

Day

Please provide brief session details

APPENDIX H – SELF REPORTING INJURY REPORT

Injury Form

Please complete this form once an injury occurs.

*Required

Name *

Name of Injury

Area of the Injury

When did the injury occur

Nature of the injury

- ☐ Soft tissue- Pulled muscle
- ☐ Soft tissue- Sprain
- ☐ Soft tissue- Strain
- ☐ Soft tissue- Tear
- ☐ Hard tissue- Break
- ☐ Hard tissue- Fracture
- ☐ Hard tissue- Stress Fracture/Hairline fracture
- ☐ Dislocation

Cause of injury

- ☐ Struck by other player
- ☐ Struck by ball/object
- ☐ Collision with other player
- ☐ Collision with fixed object
- ☐ Overexertion
- ☐ Overuse
- ☐ Landing
- ☐ Slip/trip/fall/stumble
- ☐ Other

If other please specify

Was this a Reoccurring injury

- Yes
- No

If you answered Yes, How many times has this injury occurred

Initial management of the injury

- None given
- Referred
- Rest, Ice, Compression, Elevation and Refferal
- Strapping/taping
- Rest/Monitor
- Sling/Splint/Cast/Boot
- Immobilise
- Other

If you answered other please specify

Management following the injury

- Immediate return to activity
- Return with restriction
- Rest (no training/competition)
- Unable to return at present
- Unable to return until medical clearance given

Please complete if rest from training/competition occurred

How long did you spend out of training/competition

Was it a slow return to training/competition

- Yes
- No

How long did it take to return to full training and competition

Do you feel fully recovered from the injury

APPENDIX I – PUBLICATION LIST

Articles Accepted for Publication

Millett, E., Moresi, M., Watsford, M., Taylor, P., & Greene, D. (2016). Lower Body Stiffness Modulation Strategies In Well Trained Female Athletes. *Journal of strength and conditioning research, 30*(10), 2845-2856.

Articles Under Review

Millett, E., Moresi, M., Watsford, M., Taylor, P., & Greene, D. Variations In Lower Body Stiffness During Sports Specific Tasks In Well Trained Female Athletes. *Sports Biomechanics.*

Conference Proceedings

Millett, E., Moresi, M., Watsford, M., Taylor, P., & Greene, D. (2013). *Relationship of Leg Stiffness Measures During Basic and Sports Specific Movement Tasks in High Level Netballers*. Paper presented at the International Society of Biomechanics in Sports Conference, Taipei.

Millett, E., Moresi, M., Watsford, M., Taylor, P., & Greene, D. (2014). *Influence of Athletic Training on Leg and Joint Stiffness in High Level Netballers*. Paper presented at the International Society of Biomechanics in Sports Conference, Johnson City.

Millett, E., Moresi, M., Watsford, M., Taylor, P., & Greene, D. (2015). *Relationship of Leg and joint stiffness during basic and sports specific tasks in high level athletes.* Paper presented at the International Society of Biomechanics in Sports Conference, Poitiers.