MUSCULOSKELETAL KINETIC MODELS TO PREDICT INJURY AND PERFORMANCE IN ADOLESCENT FEMALE ATHLETES

Submitted by

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Bachelor of Applied Science (Human Movement) Honours

A thesis submitted in total fulfillment of the requirements of the degree of Doctor of Philosophy

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April 2011

Statement of Authorship and Sources

This thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or have been awarded another degree or diploma.

No parts of this thesis have been submitted towards the award of any other degree or diploma in any other tertiary institution.

No other person's work has been used without due acknowledgment in the main text of the thesis.

All research procedures reported in the thesis received the approval of the relevant Ethics/Safety Committees.

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Abstract

Background: High level adolescent female athletes in high-impact sports may be at an increased injury risk due to increased training demands coupled with pubertal growth. Participation longevity in active females requires innovative, holistic research to advance the understanding of injury prevention via longitudinal training response monitoring. Measures of musculoskeletal stiffness (MSS), which model the lower limb as a spring, may provide valuable insight on this issue. MSS has been linked to both performance and injury through cross-sectional and retrospective study designs. This thesis aimed to longitudinally investigate measures of MSS, jump performance and injury in adolescent females from high-impact, low-impact and non-sporting groups.

Methods: Participants from high impact sports (gymnastics, athletics), a low impact sport (water polo), and non-sporting controls were recruited for reliability (n=16), baseline (n=113) and longitudinal (n=83) studies. A range of jump tests were performed on two portable force plates, with a focus on self-paced repeat jumps for the baseline and longitudinal (12 months) studies. MSS was calculated for short (CJb) and long effort (CJb30) continuous bent-knee repeat jumps; and short effort continuous straight-leg repeat jumps (CJs). Retrospective injury, maturational status, training hours and nutritional habits were surveyed together with injuries during the 12 month test period. Reliability statistics included intraclass correlation coefficients (ICC), coefficient of variation (CV%), percentage bias (%Bias) and Cohen's effect size (ES). Baseline and longitudinal statistical analyses included analysis of covariance (ANCOVA) and repeated measures analysis of covariance (ANCOVA) controlling for jump frequency and body mass, linear regression models, receiver operator characteristic (ROC) curves, and logistic regressions.

Results: With appropriate data reduction MSS measures used in this thesis indicated acceptable reliability (Intra-Trial: ICC: 0.98, CV%: 9.5-9.8%; Inter-Day: ICC: 0.66-0.92, CV%: 9.1-15.2, %Bias: 1.6-16.7, ES: -0.1-0.5). Significant MSS differences were identified between high-impact athletes (e.g. gymnasts: CJs k_{vert} = 24.16 kN/m, track and field CJs k_{vert} = 25.52 kN/m) and controls (e.g. CJs k_{vert} = 14.97 kN/m), with low-impact athletes demonstrating moderate MSS levels (CJs k_{vert} = 20.26 kN/m). High-impact athletes displayed greater increases in MSS when fatigued. Longitudinally the track and field athletes exhibited increased MSS (19-37%). Whereas gymnasts and water polo players showed little change (-11.3-7.7% and 3.4-15.9% respectively) Non-sporting participants had moderate increases (1.4-31.7%). Gymnasts and water polo athletes displayed similar longitudinal changes in MSS under fatigue. However, track and field athletes displayed reduced longitudinal MSS increases under fatigue. Prospective injury results indicated high incidence of lower limb musculoskeletal injuries in high-impact athletes. Higher MSS during the CJb and CJs jump tasks significantly predicted 74% of lower leg and 77% of overuse injuries respectively. Approximately 87% of fractures were predicted by bone strength and CJb30 stiffness change. Although not statistically significant, previous acute injury history and lower CJs stiffness suggested increased acute injury risk.

Discussion: Sport-specific differences in MSS measures and jump performance may reflect more effective elastic energy storage and utilization. Stiffness increases under fatigue may enable the maintenance of jump performance, but also place high-impact athletes under increased injury risk. Longitudinal changes in MSS only partially reflected the expected pattern of stiffness change. It's suggested that increased growth observed in the gymnasts 'outpaced' any training effects. Reductions in relative jump performance and stiffness measures may reflect increased growth rather than poor training adaptation. Differences between the jump tasks and

participant group results suggest potential sport-specific MSS adjustments. The present results support previous retrospective literature with stress-related overuse injuries predicted by greater levels of stiffness and lower levels of stiffness suggesting acute injury risk. Although the exact mechanisms are unclear, increased forces and loading rates associated with greater stiffness levels may overload the musculoskeletal system and result in overuse injury. In contrast, less stiffness may increase acute injury risk due to increased ranges of motion and poor elastic energy transfer.

Conclusions: MSS appears related to jump performance and injury risk in adolescent females which is influenced by sport-specific training. However, a complex interaction between growth, training and MSS appears evident. Coaches should be aware of the potential impact of growth on training and performance outcomes in adolescent athletes. Specific measures of MSS appear good predictors of lower limb injury in high-impact adolescent athletes. These measures have potential for both talent and injury risk identification within adolescent female high-impact athletes.

Statement of Appreciation

There are many people I wish to thank and acknowledge for their assistance in tackling one of the most challenging tasks I've ever undertaken.

Firstly, a huge thank you to my principal supervisor Dr Elizabeth Bradshaw and co-supervisors Professor Geraldine Naughton and Dr David Greene. Thank you for all your assistance and for being available to offer advice, wisdom and correction when needed! I would not have got there without your timely assistance. Thank you. Particular thanks to Dr 'Bones' (Greene) for his assistance and expertise in collecting and processing the pQCT data.

Additional thanks to my fellow students who assisted with all those test sessions. Particular thanks to Ms Lauren Burt and more recently Mr Paul Taylor for their assistance with both testing and also in making the days spent on the whole process enjoyable, even amidst the 'chaos'!!

I'd like to also specifically thank all of the organizations who greatly assisted and financially supported this project; the Australian Research Council, the New South Wales Sporting Injuries Committee, Athletics Australia, Gymnastics Australia, the New South Wales Institute of Sport, New South Wales Water Polo, Santa Sabina College and the Australian Catholic University.

A massive thanks is not enough for all of the administrators, coaches and athletes who gave of their time to assist and participate in the study. Without them there would truly have been nothing to discover!! Particular thanks must go to Mr Kenneth Graham, Mr David Tarbotton, Mr Ryan Moar, Mr Robert Medlicott, Mr Charles Turner, Ms Maree Gliddon and the staff at Santa Sabina, Ms Lisa Gawthorp and Ms Keren Faulkner and the staff at Gymnastics Australia for their extremely generous support of me and this project. I trust that some of the findings of the project will go at least some way to assisting you all in reaching your sporting goals.

It would be remiss of me not to thank my family. To Mum, Dad, Narelle and Andrew, thank you for your continued support and all the sacrifices you have made along the way to give me the opportunities I have had. I am truly blessed to have grown up in such a family and I would not be here if it weren't for you.

To my beautiful wife Virginia and my beautiful kids, Olivia, Joel and Anna, thank you for your unwavering support and for putting up with my relative absence in the months leading up to completion. Gin I love you and would not have made it without you. I am very much looking forward to catching up on some of the time we've missed!!

Finally, I wish to thank my Lord and Saviour without whom I would not have direction, purpose or hope.

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CHAPTER ONE

Introduction

Balancing the demands of growth and maturation with high level sports participation presents unique challenges and opportunities for the high level adolescent female athlete. With increasing specialization, training and competition loads, the potential for short and long-term benefits of sports participation exist. Positive benefits of habitual physical activity are well established and include outcomes such as increases in markers of cardiovascular health (Andersen et al., 2006), psychological (e.g. well-being; Norris, Carroll & Cochrane, 1992), improved weight management (Moore et al., 2003) and in general, improved musculoskeletal health (Khan et al., 2000). However, for the aspiring adolescent athlete, particularly females involved in high-impact sports, the increased demands of training and competition at a time of immense growth may place them at an escalated risk of injury (Purnell, Shirley, Nicholson & Adams, 2010). Despite the positive benefits of participation in sporting activities during adolescence, the underlying mechanisms leading to the potential negative outcomes from high-level participation remain unclear. There is a need for the prospective identification of these factors in high level adolescent sports.

Injury prevention among adolescent athletes is more preferable to injury treatment (Sands, 2000). However, an adequate understanding of injuries and the mechanisms underlying potential injury is required before injury prevention can become a reality. Injury surveillance into high-load, high-impact sports such as gymnastics and track and field, indicate a high prevalence of lower limb musculoskeletal injuries (Sands, Schultz & Newman, 1993; Zemper, 2005). Research into the specific injuries sustained in gymnastics identifies a high incidence of knee and ankle injuries (Kirialanis, Malliou, Beneka, & Giannakopoulos, 2003). Whereas epidemiological research on Australian track and field injuries highlights stress-related injuries and hamstring strains as among the most common (Bennell & Crossley, 1996). Exposure to increased levels of training has been shown to increase the risk of stress fracture in pre-adolescent and adolescent female athletes (Loud, Gordon, Micheli, & Field, 2005). Increased training load has also been linked with soft-tissue injuries in runners (Yeung & Yeung, 2001). Although increased load may place athletes at increased injury risk, participation in high-impact sports, particularly gymnastics and track and field, may place these athletes at increased stress-related injury risk independent of age and training load (Loud et al., 2005). Additionally the magnitude of loading may be of critical importance (Edwards, Taylor, Rudolphi, Gillette & Derrick, 2010). An athlete's ability to manage loading during ground contact in high impact sports may provide the key to identifying athletes at higher risk of injury.

Measures of musculoskeletal leg stiffness have been used to assess force attenuation characteristics during dynamic ground contacts typical of those observed in sports such as gymnastics and track and field. By modelling the joints, muscles and tendons of the lower limb as a simple spring, the relative compliance or resistance of this 'spring' under force application can be quantified. Generally increased musculoskeletal stiffness (MSS) has been associated with increased performance measures including stride frequency (Farley & Gonzalez, 1996), running velocity (Kuitunen, Komi & Kryolainen, 2002) and running economy (McMahon & Cheng, 1990). However, high levels of MSS can be detrimental in some higher load tasks (Walshe & Wilson, 1997). Measures of MSS are also linked with increased injury risk. Increased MSS may lead to increased risk of overuse and stress-related injury due to higher forces and loading rates (Butler, Crowell & Davis, 2003). Conversely, lower MSS may predispose an athlete to more acute, soft-tissue injuries (Butler et al., 2003). Thus, an optimal level of MSS may exist to enhance performance and reduce the risk of injury. However, there is an urgent need for the longitudinal assessment of the relationship of MSS with performance and injury in order to identify potential ‘safe’ stiffness zones. Particularly for adolescent female athletes who may be at increased risk of injury, the identification of potential ‘safe’ levels of lower limb MSS is of critical importance. Measures of lower limb MSS in high-impact adolescent athletes may provide important information for both talent identification and detection of ‘at risk’ junior athletes. However, both normative data and prospective links to injury within these specific populations are lacking.

The main objective of the present thesis was to longitudinally demonstrate MSS among adolescent female athletes and non-athletes to identify differences related to specific sport participation during maturation, and potential links with increased injury risk.

1.1 Limitations

The following limitations are acknowledged:

- Participants completed their normal training and competition activities across the duration of the study. Potential limitations in the study lie in the inability to alter the training approach, competition priorities, coaching style and influence, relative training loads and training phase. Each factor and combinations of these factors may have influenced the results, but were beyond the scope of the study.
- Athletes were drawn from similar levels of competitive ability. However, previous training history or experience was potentially unequal among participants and may have influenced training responses, maturation, MSS and injury.
- Potential sample bias may be present in any cross-sectional study. Sport participants were conveniently recruited predominantly through the coaches, coordinators and programs associated with the NSW Institute of Sport. Non-sporting participants were recruited from a local high school. Any potential sample bias in the recruitment process may have influenced the results of the study.
- Track and field participants were recruited from all track and jump event groups and numbers of participants were not evenly distributed across event groups. Any potential bias towards any specific event group may have influenced the results for this particular sub-population.
- The specific MSS measures used in the present study were considered typical of the underlying fundamentals of sports performance. However, stiffness was not directly measured during each group's specific sporting activity.

- Any potential influence of hormone changes on the stiffness and performance measures due to fluctuations in the menstrual cycle were not possible to monitor within the scope and time restrictions of the present study.
- Whilst care was taken to ensure the accuracy of the questionnaires used in the present study, information on nutrition, maturation, training hours and activity, and injuries were self-reported. These measures may be somewhat limited by recall accuracy and validation checks were not used.
- Self-reported questionnaires were completed to help describe extra-curricular or outside of sport activities. However, participation in other activities outside of the sport or normal school classes may have influenced the results.
- Training hours were considered as a measure in the present study. Nevertheless, training hours may be limited in quantifying the actual volume of loading experienced from training and its subsequent potential effect on stiffness and injury. The use of hours of training may be limited in accurately estimating training load.
- Any potential impact of emotional or psychological factors on performance and injury were also beyond the scope of this study.

1.2 Delimitations

The following delimitations were applied:

- Participation was restricted to females.
- Participants were aged between 12 and 18 year of age.
- Participants had to be free of injury at the commencement of testing.
- Participants were limited to four specific sub-populations of adolescent females; track and field athletes, gymnasts, water polo players and non-sporting participants.
- Participants from sporting populations had to be of sufficient proficiency to be considered as national level athletes. This corresponded to having at least obtained the standard for entry to the national junior championships for track and field, compete at International level 8, 10, junior or senior level in gymnastics, and be part of the state U/17 or NSW Institute of Sport squad for water polo.
- Track and field athletes were restricted to track events, jumps and multi-event disciplines only.
- Testing was limited to a 12 month period with two main test sessions at baseline and 12 months.
- Biomechanical analysis of MSS was restricted to field-based repeat jumping activities.
- Jumps were selected as common methods of assessing lower limb MSS in similar groups of athletes and included continuous bent-knee repeat jumps (CJb), continuous 'straight-leg' repeat jumps (CJs), and continuous bent knee jumps for thirty seconds (CJb30).

- Injuries were limited to recalled injuries that occurred in the lower limb and were directly sport-related during the previous two years prior to the baseline testing (retrospective) and during the 12 months of the study (prospective). This included hip or pelvic injuries but excluded any injuries considered back-related.

1.3 Definitions

Adolescence: the transition from childhood to adulthood, marked by significant increases in growth, changes to body shape and proportions along with physical and sexual maturation.

High Level: in the present study 'high level' is defined as an athlete who was competing at a national level or above, relative to age. For track and field athletes, this corresponded to being at the standard to qualify for the national junior championships in their respective age group and event. For gymnastics the national level was represented by classification in International level 8 or above. Water polo players were considered high level if they were selected to compete in the U/17 squad for the national water polo championships or were a member of the NSW Institute of Sport water polo squad.

Fatigue: a decline of physical performance and/or capacity due to a reduction in physiological functioning. In the present study this was defined as the final ten jumps during a series of continuous jumps for a 30 second duration.

Growth: the physical process in which an increase in size, length, or mass occurs.

Injury: any physical problem as a direct result of participation in an athlete's chosen sport or activity, resulting in that athlete missing or modifying a subsequent training session or competition.

Maturation: the physical process of biological transition from childhood to adulthood.

Musculoskeletal Stiffness: the combined actions of the joints, muscles and tendons of the leg to resist or comply with an external application of force (such as during ground contact).

Non-sporting: a non-sporting participant was defined as an adolescent who did not participate in more than 4 hours of organized sporting activity outside of normal school activities.

Stiffness: the resistance or compliance of a spring or modelled spring to the application of an external force. This is quantified as a ratio of the peak force applied, in Newtons (N), divided by the spring's subsequent deformation in metres (m).

Training: any structured activity designed and undertaken to elicit a positive physical or technical change to sports performance.

CHAPTER TWO

Literature Review

2.1 The Adolescent Athlete

2.1.1 Growth during Adolescence

The transition from childhood to adulthood, known as adolescence, is marked by a period of immense growth and maturation (Tanner, 1978). During adolescence numerous changes occur across a number of dimensions; physical, emotional and cognitive. The onset of the adolescence growth spurt can vary widely among individuals but generally corresponds to a skeletal age of approximately 11 years in females and 13 years in males (Rogol, Clark & Roemmich, 2000). Some of the significant changes that occur in both males and females during this period include a rapid increase in skeletal height, weight gain, sexual maturation, marked changes in body composition and changes in strength, motor control and aerobic capacity (Malina, Bar-Or, & Bouchard, 2004). For females, the average peak height velocity during adolescence is 9 cm/year at age 12 (Rogol et al., 2000). This intense increase in height is generally finished by approximately 15 years of age (Rogol et al., 2000). Approximately fifty percent of adult body weight is also gained during adolescence with a peak weight gain of 8.3 kg/year occurring at about 12.5 years of age (Rogol et al., 2000).

Development during adolescence also involves marked changes in the proportions and distribution of skeletal muscle, water, bone and adipose tissue that will later define the differences observed between adult males and females (Malina et al., 2004). In females, sexual maturation is evident by an increase in breast size, development of pubic hair and the onset of menarche. The onset of menarche generally occurs late in the growth process and occurs at approximately 13 years of age (Malina et al., 2004). Muscular strength measures indicate that a general peak occurs around the same time of peak height velocity in females (Malina et al., 2004). However, coinciding with these maturation-related physical changes is a period of decline in balance and fine motor control (Malina et al., 2004).

During adolescence, bone mineral content (BMC) markedly increases. Greater than 90% of the peak bone mass (PBM) accumulates by age 18 for adolescents experiencing normal growth patterns (Nattiv & Armsey, 1997). The PBM value represents a consequence of the net accrual of bone during childhood and the balance between accrual and resorption in adulthood (Bass, 2000). For females, the three to four years immediately following puberty is critical for accumulating approximately one-third of their total peak bone mass (Rogol et al., 2000). A delay in puberty or subsequent menarche may result in reduced bone mineral accrual during this time which, in turn, may result in compromised bone health in later life (Rogol et al., 2000). Bone development in adolescence differs between males and females. Females experience an accrual of bone mass which thickens the cortical wall in conjunction with some widening of the medullary cavity during early adolescent growth (Seeman, 2002; Figure 2.1). For males, bone accrual occurs on both endosteal and periosteal surfaces resulting in a thicker bone and a larger medullary cavity (Malina et al., 2004; Figure 2.1). This larger cross-sectional area results in a greater displacement of bone further from the neutral axis which thereby produces greater bone strength (Seeman, 2002).

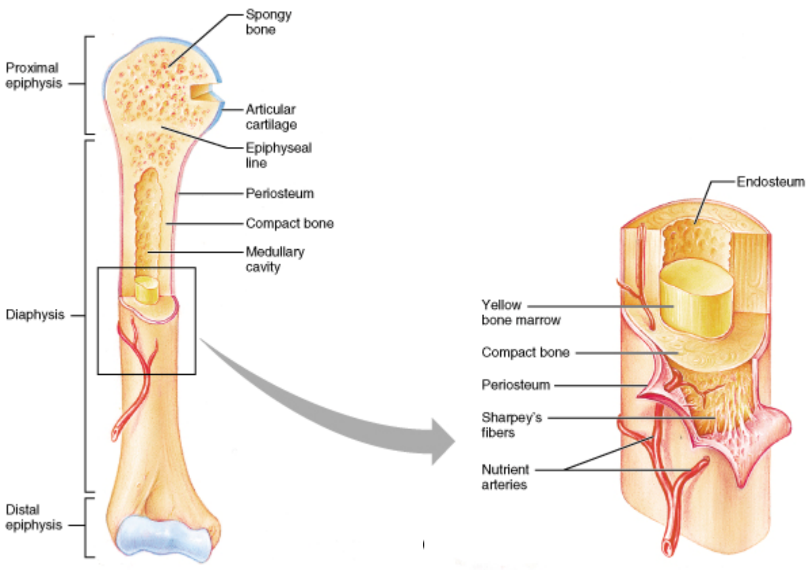

Figure 2.1 Anatomy of the long bone (image from Benjamin Cummings). Compact bone is also known as cortical bone, which is dense, hard bone tissue. Likewise, spongy bone is also known as trabecular bone which is soft and spongy bone tissue.

Two of the major influences on adolescent growth are nutrition and exercise (Rogol et al., 2000). A combination of reduced caloric intake and/or particular nutritional elements required for growth (e.g. calcium for bone growth) and the high energy expenditure of high level sports, have the potential to negatively impact on the growth status of adolescent females (Nattiv & Armsey, 1997). High level female athletic populations can experience delays in growth and sexual maturation in sports such as gymnasts and long-distance running (Theiwtz, Howald, Weiss & Sizonenko, 1993; Bass et al., 2000; Daly, Caine, Bass, Pieter & Broekhoff, 2005). However, the extent of the impact of high-level sport participation on maturation and the possible underlying causal mechanisms, are still largely unknown (Rogol et al., 2000). The relationship between low energy availability, compromised bone health and menstrual irregularities has been referred to as the 'female athlete triad' and is identified as a short and long-term health concern, particularly in active females (Birch, 2005).

For the female adolescent athlete, it appears that there is a complex interaction between the demands of aspiring high level sports performance and the demands of normal growth and maturation. In addition, the rapid changes to muscle tissue, strength, coordination, bone and tendons have the potential to influence sport-specific biomechanics, which may in turn affect the performance and injury risk of adolescent female athletes.

2.1.2 Impact of Physical Activity during Adolescence

Numerous positive benefits of habitual exercise participation have been established which have both short and long-term benefits for the adolescent athlete. Improvements in markers of cardiovascular health (Anderson et al., 2006), self-esteem and psychological benefits (Norris et al., 1992), strength gains (Morris, Naughton, Gibbs, Carlson & Wark, 1997; Witze & Snow, 2000) and in particular gains in bone strength and mineral content have been documented (Greene et al., 2005).

Exposure to high-impact musculoskeletal loading through sports participation is potentially beneficial during growth. Weight bearing activity has a positive influence on BMC during growth (Proctor, Adams, Shaffrath & Van Loan, 2002; Bailey, Faulkner, & McKay, 1996; Faulkner et al., 1993). Accrual of this BMC is vital for osteoporosis prevention. A 10% increase in peak BMC reduces the risk of fracture in later life by half and also delays the onset of osteoporosis by an estimated 13 years (Hernandez, Beaupre, & Carter, 2003). A reduction in osteoporosis and/or bone fracture risk may improve quality of life (Witze & Snow, 2000; Frederickson, Ngo, & Cobb, 2005). Research into the benefits of mechanical loading from sport participation suggests positive bone-building potential (Bass et al., 2002; Grimston, Willows, & Hanley, 1993; Proctor et al., 2002). Despite numerous epidemiological studies on injury rates, few studies have examined adolescent skeletal responses to mechanical loading at the aspiring elite level (Duncan et al., 2002; Greene et al., 2005).

Multiple positive outcomes from participation in weight-bearing physical activity may result from the increased training loads in high-impact sports such as athletics and gymnastics. But for the more serious adolescent athlete, participation can also have potential negative outcomes. Maturational disturbance or delay, overtraining and/or burnout and an increase in injury risk may be associated with participation at higher levels (Rogol et al, 2000; Maffulli, Baxter-Jones & Grieve, 2005). Whilst there remains debate about the long-term impact of maturational delay on the health and well-being of the adolescent female athlete (Caine, Lewis, O'Connor, Howe & Bass, 2001), an increase in injury risk and risk of re-injury including longer term injury problems, particularly for musculoskeletal injuries, remains real. For athletes involved in high-impact sports, such as gymnastics, the period of adolescence is a critical time where the impact of growth may create increased injury risk with increasing levels of training (Purnell et al., 2010). It would appear that a threshold exists where the positive potential of bone building due to the nature of the activity, gives way to increased injury risk where the demands of the activity exceed the structural capacities of the athlete.

2.1.3 Injuries in High-Impact Adolescent Sporting Populations

Sporting injuries occurring in females aged 5-14 years are among the most expensive in terms of medical cost (Medibank Private, 2004). In addition, musculoskeletal injuries are among the most common types of injury in adolescent populations, with muscular strain the most common category of injury in adolescent track and field athletes (Zemper, 2005). Research into injury incidence among Australian track and field athletes indicates a high number of injuries experienced (76% of athletes injured in a 12 month period) with the majority of injuries occurring in the leg, thigh and knee (Bennell & Crossley, 1996). The most common injuries were stress-related overuse injuries and hamstring strain with a rate of injury recurrence exceeding 30%. Similarly, investigations into injury rates and common injury sites in gymnastics also reveal high injury rates (Sands et al., 1993) with the most common injuries occurring at the ankle and knee joints (Kirialanis et al., 2003). Research into lower limb overuse injuries and stress fracture in females involved in high-impact sports suggest several potential associated risk factors including bone strength and density, body size and composition, muscular strength and endurance, menstrual disturbance, family history and nutritional factors (Bennell, Matheson, Meeuwisse & Brukner, 1999; Loud, Micheli, Bristol, Austin & Gordon, 2007). Exposure to increased loading is suggested as a risk factor in both stress fracture (Bennell et al., 1999; Jones, Thacker, Gilchrist, Kimsey & Sosin, 2002) and lower limb soft tissue injuries (Yeung & Yeung, 2001). Investigations into injury rates among high level young athletes involved in non-contact sports also suggests an increased risk of injury with increased exposure to training (Maffulli et al., 2005). Particularly for stress related injuries, training hours of greater than 16 hours per week have been shown to increase risk of injury in preadolescent and adolescent girls (Loud et al., 2005). However, it has also been suggested that girls involved in high-impact sports are at greater injury risk, independent of age and hours of activity per week (Loud et al., 2005). This would suggest that it’s not just the training load, but the magnitude of the loading that may be important in injury risk exposure among adolescent female athletes. It’s postulated that overuse injury development, in particular stress fracture, may be more dependent on loading magnitude than loading exposure (Edwards et al., 2010). With ground reaction forces during high-impact sports, such as jumping in track and field and tumbling and landing in gymnastics, potentially reaching fourteen to fifteen times body weight (Perttunen, Kryolainen, Komi & Heinonen, 2000; Marinsek, 2010), the impact of loading during these sports is not surprising. However, despite the high forces involved and the apparent link between the relative loading of high-impact sports and increased injury risk, research into the relationship between ground reaction forces and overuse injuries in athletes provides conflicting findings (Grimston, Engsberg, Kloiber & Hanley, 1991; Crossley, Bennell, Wrigley & Oakes, 1999; Bennell et al., 2004; Willems, Witvrouw, De Cock & De Clercq, 2007). It is possible that the way an individual is able to attenuate the high forces produced during such activities, rather than the magnitude of the forces themselves that may be critical in injury risk identification.

Measures of lower limb musculoskeletal stiffness (MSS) endeavour to quantify the bodies' ability to deal with ground contact and may provide a key in identifying potential injury risk at such a critical period in a young athlete's career. Exploration of an athlete's biomechanics, via the quantification of MSS during ground contact in typical functional activities, may provide further insight into understanding the complex interactions of growth, loading and injury risk that surround the high-level adolescent female athlete. With limited longitudinal research to date, there is a need to investigate the impact of high level sport on growth and maturation and injury in the high level adolescent athlete. The ability to establish a model capable of predicting an increase in injury risk may aid in guiding the high level adolescent athlete and coach in training and competition prescription at such a crucial time in their sporting career. Such a tool may hopefully assist in increasing the success, longevity and wellbeing of many of our aspiring talented athletes.

2.2 Musculoskeletal Stiffness

2.2.1 Defining Musculoskeletal Stiffness

Almost all functional athletic activities are the result of a combination of vertical, horizontal, and/or mediolateral ground reaction forces (Maulder & Cronin, 2005). The effective application of these forces enables the generation (initiation) or the continuity of highly coordinated multi-joint movement actions such as running and jumping, which serve as the foundation of many sport activities, such as gymnastics and track and field. Coordination and control of the lower limb's joints, muscles and tendons is required for the successful and effective completion of landings and takeoffs (Funase et al., 2001) during jumping and running. Control of the hip, knee and ankle joints during ground contact serves to attenuate the body's mass with the forces applied to it. The ability of the musculoskeletal system to deform or resist deformity under external force application is referred to as MSS. The evaluation of force attenuation ability during functional activities via MSS assessment may provide a valuable key to understanding the impact of load during high-impact sports on injury risk.

The foundation of MSS is established in Hooke's Law. Hooke's Law quantifies the relationship between force, deformation and stiffness in objects that absorb and return elastic energy (Butler et al., 2003). The mass-spring model has gained increased attention in the exercise science literature in recent years via application of a rearrangement of Hooke's Law to human motion. By modelling the muscles, tendons and joints of the leg as a simple spring that attenuates forces between the ground and bodies' centre of mass, the stiffness of this 'spring' can be assessed (Figure 2.2). It is argued that the mass-spring model oversimplifies the complexities and tissue properties of the lower limb and therefore represents only 'quasi-stiffness'

(Latash & Zatsiorsky, 1993). However, to adequately model the joints, muscles, tendons and their interaction within the lower limb would be extremely complex with numerous calculations and assumptions which makes it impractical (Butler et al., 2003). Common models for musculoskeletal simulations represent the interaction of the musculoskeletal system as a combination of tendon, passive and contractile elements working in series and parallel (Figure 2.3; Erdemir, McLean, Herzog & van den Bogert, 2007). Musculoskeletal stiffness research has investigated the influence of these individual elements including ultrasonic assessment of Achilles tendon stiffness (Kubo, Kawakami & Fukunaga, 1999; Burgess, Connick, Graham-Smith & Pearson, 2007; Kubo et al., 2007) and measures of passive stiffness (Magnusson, 1998). However, typical measures of MSS represent the coordination and combination of all the suggested stiffness elements that govern the interaction of force and the body's mass during ground contact (Butler et al., 2003).

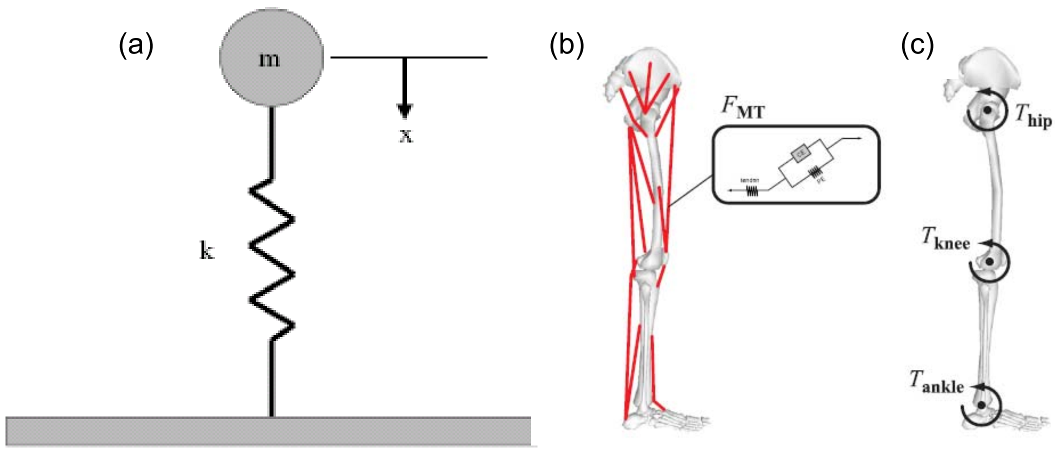

Figure 2.2 Mass-spring model (a) represented by a single spring that attenuates force between the body's mass and the ground during contact (b) including all joints, muscles (passive and contractile elements) and tendons. (Source: Butler et al., 2003 and Erdemer et al., 2007). The leg spring (c) can be modified by the torque produced at the hip, knee and ankle joints. For example, in countermovement (bent leg) jumping the hip and knee joints are dominant in creating torque and levels of leg stiffness. In hopping (ankle repeat jumps), the hip and knee joints are braced (constant torque) and the ankle controls the level of stiffness of the leg system.

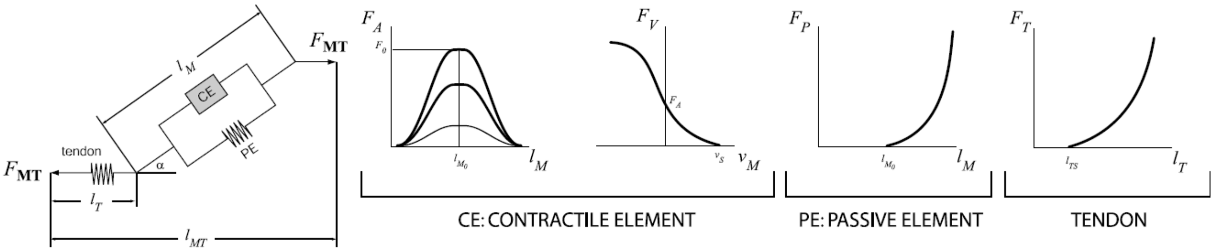

Figure 2.3 Contractile (CE), passive (PE) and tendon elements of common musculoskeletal simulation models that contribute to the overall musculoskeletal stiffness of a typical segment (i.e. lower limb). (Source: Erdemir et al., 2007)

Assessment of the force-displacement curves within much of the stiffness literature would suggest that, at least for repeat jumping activities, jumping performed at or above a self-selected jump frequency (approximately 2.2 Hz for adults) appears to reflect expected ‘spring-like’ behaviour (Farley, Blickhan, Saito & Taylor, 1991; Figure 2.4). True mass-spring behavior is evidenced by a reduction of overall spring length with the application of an external force, and the subsequent storage of elastic energy. Once the maximal spring compression and corresponding peak force is reached, the recoil of the spring is characterized by a continual reduction in the external force, as the spring releases its stored elastic energy, and lengthens until it returns to its original state. Despite the foundations of MSS being the same, a wide variety of methodologies and stiffness calculations litter the literature. Although often reflecting variations in methodology, these differences make the comparison and evaluation of the stiffness literature quite a challenge.

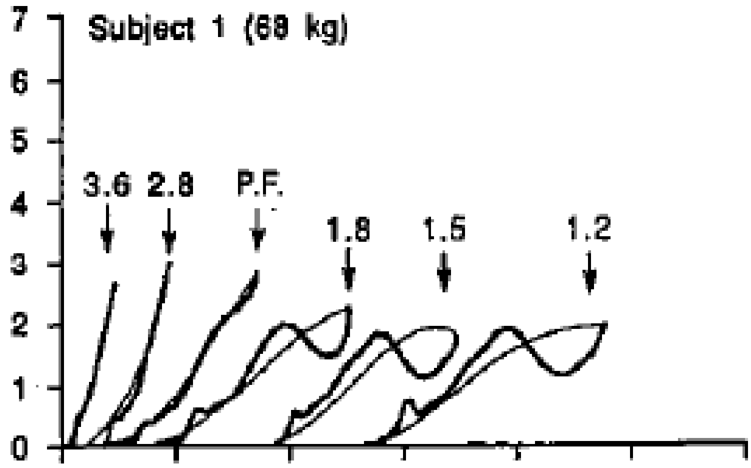

Figure 2.4 Sample force-displacement curve during double-leg repeat jumping at various frequencies. Curves at the self-selected frequency (P.F.) and above (3.6 & 2.8) appear to closely resemble simple spring-like behavior. (Source: Farley et al., 1991).

2.2.2 Test Methodologies in Musculoskeletal Stiffness Research

Musculoskeletal stiffness has been investigated in relation to several factors including performance and injury risk (Butler et al., 2003). Performance studies have investigated MSS in relation to parameters such as jumping ability (Laffaye, Bardy & Durey, 2005), reactive jumping ability (Arampatzis, Schade, Walsh & Bruggemann, 2001) and gait parameters such as running economy (Dalleau, Belli, Bourdin & Lacour, 1998), stride length (McMahon, Valliant & Frederick, 1987), stride frequency (Farley & Gonzalez, 1996) and running velocity (Kuitunen et al., 2002). Although little direct research exists, lower limb stiffness has also been investigated in association with potential injury risk factors such as gender differences (Granata, Padua & Wilson, 2002b), increased knee or ACL injury risk (Padua, Carcia, Arnold & Granata, 2005) and arch structure in runners (Williams, McClay-Davis, Scholz, Hamill & Buchanan, 2003). In conjunction with the varied avenues of research, MSS has been quantified within several different functional tasks across the literature.

2.2.2.1 Functional Tasks in Musculoskeletal Stiffness Assessment

The mechanisms and influence of MSS on a range of functional activities have been explored in the literature. Lower limb stiffness evaluation during double-leg vertical jumping (sometimes referred to as bi-lateral or double-leg hopping) appears to be the most common test methodology employed. However, alternate test methodologies include the assessment of lower limb stiffness during gait and sprinting both over-ground (Ferris, Louie & Farley, 1998) and on a treadmill (Chelly & Denis, 2001), drop jumps (Arampatzis et al., 2001), jumps using a sled apparatus (Kuitunen, Kryolainen, Avela & Komi, 2007), during single-leg jumps (Laffaye et al., 2005) and perturbation during isometric contractions (McLachlan, Murphy, Watsford & Rees, 2006).

The assessment of lower limb MSS during isometric contractions following an external perturbation or applied force endeavors to study the stiffness properties of the musculotendinous unit (Murphy, Watsford, Coutts & Pine, 2003). By applying an external force to the limb (generally the leg) during an isometric contraction, evaluation of the ‘disturbance’ (shortening of the leg ‘spring’) and its relationship to the force applied can give an indirect assessment of the stiffness of the contractile and structural components of the leg. Perturbation studies have investigated MSS for both the entire leg including ankle, knee and hip joints (Walshe, Wilson & Murphy, 1996), lower limb and calf (McLachlan et al., 2006) and knee flexor/extensor musclulature (Granata, Wilson & Padua, 2002a). Although assessing similar components of leg stiffness, this area of research differs from the more ‘functional’ stiffness literature which seeks to quantify the combination of the musculotendinous unit and the coordination and motor control of the leg muscles under external force application during functional activities such as jumping or running.

Gait, generally running or sprinting, has been used to assess the relationship of lower limb MSS with a number of variables including stride frequency (Farley & Gonzalez, 1996), stride length (Derrick, Caldwell & Hamill, 2000) and running economy (Dalleau et al., 1998). Generally a range of velocities from sub-maximal to maximal or specific variations of stride length or frequency have been tested using either overground (Cavagna, Franzetti, Heglund & Willems, 1988) or treadmill running (Dalleau et al., 1998). Musculoskeletal stiffness during running gait differs from that during jumping tasks in that the compression of the leg 'spring' is not adequately represented by the 'centre of mass' vertical displacement alone. At initial ground contact and take-off, the leg strikes with the foot in front of and behind the body's centre of mass respectively (McMahon & Cheng, 1990). Thus, for the correct evaluation of stiffness during gait, the compression of the leg must be considered in the stiffness equation and is often referred to as leg stiffness (k_{leg}).

Evaluation of MSS during double-leg repeat jump tests have been widely utilized in the literature and represents a simple yet effective way of quantifying lower limb stiffness during a closed-chain, multi-joint activity. Its simplicity and ability to reflect some of the key foundational elements (i.e. elastic energy storage, force absorption and propulsion) related to sports performance have made it attractive as a test modality. However, even within this type of test, further variation exists. Generally, a series of continuous jumps is completed at either a set (e.g. 2.5 Hz, usually controlled via the use of a metronome) or self-selected jump frequency. Frequencies assessed range from as low as 1.2 Hz to as high as 3.6 Hz (Farley et al., 1991), although it is suggested that only jump frequencies at or above the self-selected frequency (approximately 2.0-2.2 Hz) are reflective of true mass-spring behavior (Farley et al., 1991). Higher frequencies, above 3.0 Hz, are reportedly too difficult to execute in endurance and weight-trained athletes (Hobara et al., 2008).

Although jump frequency and leg stiffness are related (Farley et al., 1991), the use of self-selected jump frequency tasks, when participants can choose their preferred frequency and stiffness strategy, may provide measures of leg stiffness more reflective of ‘everyday’ force attenuation patterns (Padua et al., 2005). Previous literature has shown consistency in self-selected jump frequency (approximately 2.2 Hz; Farley et al., 1991). In addition to differences in jump frequency, specific variations of double-leg repeat jumps designed for distinct populations have been investigated. Studies into the MSS characteristics of gymnasts have utilised a modified ‘straight-leg’ repeat jump test where minimal knee flexion during contact was performed (Bradshaw & Le Rossignol, 2004). The modified straight-leg assessment was employed to specifically target the ankle contribution to stiffness changes and to elicit potential variations in stiffness between individuals under differing constraints. Studies have also investigated stiffness changes under fatigue by having an extended period of repeat jumps (Kuitunen et al., 2007) or by some form of intervention followed by repeated testing (Padua et al., 2006). Additional research has investigated stiffness during continuous horizontal forward jumping (Farley et al., 1991), during drop jumps (Arampatzis et al., 2001) which add an additional reactive component, during single-leg jumps for height (Laffaye et al., 2005) and during double-leg repeat jumps on a sled apparatus (Harrison, Keane & Coglan, 2004). As with double-leg repeat jumps, these studies are essentially attempting to measure the general musculotendinous unit and additional muscular control of leg stiffness during jumping with slight variations in technique or mode of jumping.

As with the diversity in leg stiffness activities assessed in the literature, variations in the stiffness calculation and data reduction methods also exist. Often this reflects variations in test methodology; however variation within similar test protocols is also evident. Despite some literature indicating ‘near identical’ results for different calculations of lower limb stiffness (Padua et al., 2005), other authors suggest that different MSS calculations may result in very different stiffness values and warrant consideration (Butler et al., 2003). In addition to the discrepancies within the potential impact of the stiffness calculation utilised, some MSS calculations may also be inappropriate for the methodology being used.

2.2.2.2 Musculoskeletal Stiffness Calculations

As with the variations in test methodology, multiple variations in the calculations used to quantify lower limb MSS are evident in the literature. Although there are multiple equations within particular research areas, MSS calculations align with three major categories based on their application; vertical stiffness measures, running or gait stiffness measures and joint stiffness measures (Table 2.1).

Table 2.1

Musculoskeletal Lower Limb Stiffness Calculations during Ground Contact in Repeat Jumping.

Vertical Stiffness (k_{vert})	**Reference**
$$\mathbf{k_{vert} = F_{max} / \Delta y} \quad (1)$$ where F_{max} = max vertical force; Δy = vertical displacement of the centre of mass from contact to its lowest point.	McMahon & Cheng (1990)
$$\mathbf{k_{vert} = F_i / \Delta y} \quad (2)$$ where F_i = vertical force at the point where power becomes positive (eccentric-concentric transition phase of contraction); Δy = vertical displacement of the centre of mass from contact to its lowest point.	based on Bosco (1999)
$$\mathbf{k_{vert} = m(2\pi/P)^2} \quad (3)$$ where m = mass of the body; P = period of the vertical vibration.	Cavagna et al. (1988)
$$\mathbf{k_{vert} = m\omega_0^2} \quad (4)$$ where m = mass of the body; ω_0 = natural frequency of oscillation.	McMahon et al. (1987)
$$\mathbf{k_{vert}} = \frac{\mathbf{m \times \pi(T_f + T_c)}}{\mathbf{T_c}^2 \left(\frac{\mathbf{T_f + T_c}}{\boldsymbol{\pi}} - \frac{\mathbf{T_c}}{\mathbf{4}}\right)} \quad (5)$$ where m = mass of the body; T_c = ground contact time and T_f = flight time.	Dalleau et al. (2004)

Running Stiffness (k_{leg})	Reference
$k_{leg} = F_{max} / \Delta L$ (6) where F_{max} = maximum vertical force; ΔL = change in leg length ($\Delta L = \Delta y + L_o (1-\cos\theta)$ and $\theta = \sin^{-1}(ut_c/2L_o)$); Δy = maximum displacement of the COM; L_o = standing leg length (greater trochanter to floor); θ = half angle of the arc swept by the leg; u = horizontal velocity; t_c = contact time.	McMahon & Cheng (1990)
$k_{leg} = F_{max} / \Delta L$ (7) where F_{max} represents the estimated maximum vertical force $F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c} + 1\right)$; and ΔL represents the change in leg length $\Delta L = -\sqrt{L^2 - \left(\frac{vt_c}{2}\right)^2} + \Delta y_c$; where m = body mass (kg), g = acceleration due to gravity, t_f = flight time (s), t_c = contact time (s), L = standing leg length (greater trochanter to floor), v = constant horizontal velocity, Δy_c = vertical change in centre of mass displacement during contact.	Morin et al. (2005)

Joint Stiffness (k_{joint})	Reference
$K_{joint} = \Delta M / \Delta\theta$ (8) where ΔM = change in joint moment and $\Delta\theta$ = change in joint angle during the first half of ground contact	Farley et al. (1998)
$K_{joint} = 2W^{-}_{joint} / \Delta\theta_J$ (9) where W^{-}_{joint} = the negative mechanical work at the joint during the eccentric phase of contact and $\Delta\theta_J$ = change in joint angle during the first half of ground contact	Arampatzis et al. (1999)

2.2.2.2.1 *Vertical Musculoskeletal Stiffness Measures*

The most common and simplest calculation of MSS is a simple rearrangement of Hooke's law where a ratio of the peak force applied and subsequent centre of mass displacement is calculated (Table 2.1, Equation 1; McMahon & Cheng, 1990). In a task such as double-leg repeat jumping, this represents the peak force during ground contact divided by the displacement of the centre of mass from contact to its minimum point. The corresponding stiffness coefficient represents the vertical stiffness of the lower limb during contact (k_{vert}). Although some researchers have used motion analysis to calculate centre of mass displacement (Arampatzis, Bruggemann & Metzler, 1999), centre of mass displacement is typically derived via the double-integration of the force-time curve as measured by a force plate (Cavagna, 1975). This method of calculation requires only one piece of equipment and has been shown to be accurate for vertical repeat jumps (Ranavolo et al., 2008). It has been suggested that the eccentric-concentric transition force (F_i) is related to elastic energy storage and utilisation during countermovement and squat jumps (Bosco, Tihanyi, Komi, Fekete & Apor, 1982). As such, the utilisation of F_i as the numerator in the calculation of lower limb stiffness may provide a good indication of the elastic energy utilisation during reactive jumps (Bosco, 1999). In true mass-spring behavior, F_i force will be equal to the peak force and thus the result of these two equations will be equal (Farley et al., 1991). During double-leg repeat jumping lower limb stiffness is measured as the net stiffness for the joints, muscles and tendons of both legs (Latash & Zatsiorsky, 1993). Although closely related to the aforementioned formulas, the slope of the force-displacement regression line during the eccentric phase of ground contact is an additional formula that has been used to represent vertical stiffness (Padua et al., 2006). Similar values to the original peak force method (Table 2.1, Equation 4) have been reported for force-displacement regression calculations during repeat jump tasks (Granata et al., 2002b). Despite these results, the variance or similarity within different stiffness calculation values remains widely under researched.

Other measures of vertical stiffness presented in the literature have used the assumption that in a true mass-spring system motion will act in a sinusoidal nature and as such use the frequency of the movement to calculate stiffness (Table 2.1, Equations 3 and 4). Cavagna et al. (1988) used the time between the peaks of the derived velocity-time curve during contact (ie. during positive acceleration or when the force curve is above body weight) to represent half the period of oscillation (Figure 2.5). This is then used with the subject's mass to calculate MSS as per equation 3 (Table 2.1). Similarly, McMahon et al. (1987) also calculated what they termed the 'natural frequency of oscillation' which was derived from contact time and flight time information. Again this is multiplied by the participant's mass to calculate MSS. Although slightly different information is utilised to calculate each value of stiffness, this is essentially the same calculation (Farley et al., 1991). Both equations are generally used when a set frequency of movement is present, as per double-leg repeat jumps at a prescribed jump frequency. In addition, a recently proposed vertical stiffness equation requiring only contact and flight time information has been put forward (Table 2.1, Equation 5; Dalleau, Belli, Viale, Lacour & Bourdin, 2004). The advantage of the latter two equations comes from the potential to calculate MSS from simple measurements using relatively inexpensive equipment such foot switches or contact mats.

In vertical jumping tasks, such as double-leg repeat jumps, due to the vertical nature of the activity, leg stiffness and vertical stiffness measures are essentially equal (Butler et al., 2003). However, during gait related tasks, measures of vertical stiffness are inappropriate as there are both vertical and horizontal components to the activity. Thus, true measures of stiffness during gait require evaluation of the compression of the leg 'spring' as a result of the force applied during ground contact (k_{leg}). Leg compression or flexion differs from the vertical displacement of the body's centre of mass and as such musculoskletetal stiffness must be calculated slightly differently.

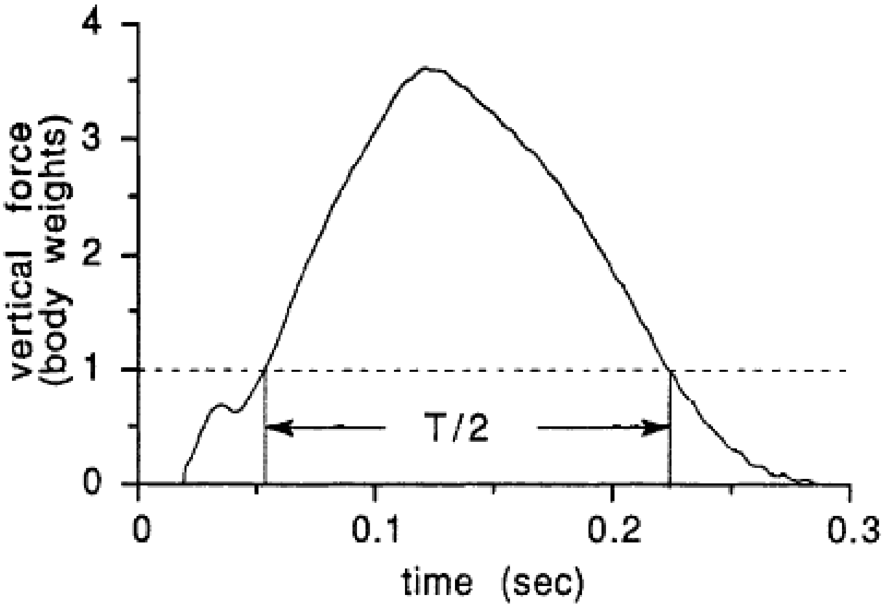

Figure 2.5 One half of the resonant frequency during ground contact (T/2) represented by the time period where the ground reaction force is above body weight. (Source: Farley et al., 1991)

2.2.2.2.2 Running Musculoskeletal Stiffness Measures

For measures of leg stiffness (k_{leg}) during gait, a ratio of the peak force applied to the compression of the leg during ground contact is calculated. The change in leg length is used in place of the vertical displacement of the body's centre of mass in the denominator of the original rearrangement of Hooke's law. The use of 2D or 3D motion analysis can be used to quantify this leg compression (Arampatzis et al., 1999). McMahon and Cheng (1990) however developed an equation that utilised horizontal velocity, angle of contact of the leg, contact time, vertical centre of mass displacement and resting leg length to calculate the change in leg length during running gait (Table 2.1, Equation 6). This required only force plate, horizontal velocity and anthropometry measures. As the pattern of gait motion becomes more vertical and less horizontal in nature (i.e. more akin to jumping vertically), the additional change in leg length approaches zero and thus the denominator displacement value becomes the equivalent of the k_{vert} equation (ie. centre of mass displacement). Although relatively widely used in the literature, it is suggested this equation may overestimate the leg compression experienced during running gait (Arampatzis et al., 1999). More recently Morin, Dalleau, Kryolainen, Jeannin and Belli (2005) proposed a 'hybrid' of Dalleau et al.'s (2004) vertical stiffness equation with McMahon and Cheng's (1990) leg stiffness equation (Table 2.1, Equation 7). The proposed leg stiffness calculation represents a stiffness calculation for gait that requires only running velocity, contact and flight time information. Morin et al.'s (2005) equation uses gait information to model the peak force and leg length change thus quantifying MSS during gait. As with Dalleau et al. (2004), this type of calculation appears attractive in its application to the field and use of relatively simple and inexpensive equipment. In addition to vertical and leg stiffness research, interest into the relative contributions of the separate joints during jumping or running has also been investigated (Farley, Houdijk, Van Strien, & Louie, 1998).

2.2.2.2.3 *Joint Musculoskeletal Stiffness Measures*

Whilst still having their origins in Hooke's law, joint stiffness measures represent yet another variation within the body of literature investigating MSS. Studies investigating the contribution of the ankle, knee and/or hip joint to gait or repeat jumping have sought to quantify joint stiffness (Farley et al., 1998). Comparisons can then be made to vertical or leg stiffness changes and assumptions made as to the relative contributions of each joint.

As with vertical stiffness measures, the simplest and most prevalent joint stiffness (k_{joint}) calculation is a rotational version of the peak force-displacement equation (Table 2.1, Equation 8). Joint stiffness is calculated as a ratio of the change in the net joint moment to the change in joint angle, from the point of contact to where the joints are maximally flexed (Farley et al., 1998). With the exception of the knee and hip joint during repeat jumps on very compliant surfaces, research indicates joint stiffness appears to behave in a spring-like manner with peak joint moments occurring at the point of maximal joint flexion and within 10% of the time of peak force and maximum leg displacement (Farley & Morgenroth, 1999). Thus it would appear, at least during repeat jumps, modelling the hip, knee and ankle joint as a rotational spring is valid. The average stiffness during this phase can also be calculated using the regression slope of the moment-angle curve which is the rotational equivalent of using the regression slope from the force-displacement curve (Muller, Grimmer & Blickhan, 2010). Arampatzis et al. (1999) also calculated joint stiffness in relation to running velocity but used a variation on joint stiffness calculations (Table 2.1, Equation 9). They calculated knee and ankle joint stiffness from a work-energy perspective equating joint stiffness as a ratio of the negative mechanical work done to the change in joint angle.

With such variation in stiffness calculations within studies investigating similar aspects of MSS, it can be difficult to compare results across the literature. To the best of the author's knowledge, only two studies appear to have directly assessed the differences between stiffness calculations (Arampatzis et al., 1999; Padua et al., 2005), with only one of these directly reporting the calculated differences (Arampatzis et al., 1999). In addition to the wide variety of test methodology and stiffness calculations used throughout the MSS research, closer review of the literature reveals further variation within the data reduction process with no apparent information on its impact on the stiffness values obtained. Even within the most common test methodology, the assessment of MSS during double-leg repeat jumps, there is wide variety in the data reduction criteria and methods employed.

2.2.2.3 Stiffness Data Reduction Methods

Although much of the literature assessing lower limb stiffness during repeat jumping includes some detail on the method of stiffness calculation for a single contact, the data reduction process is often less transparent. Presumably this stems from the need to keep manuscripts succinct and avoid reader confusion through the use of overt detail, and/or where manufacturer software has been used (e.g. Kistler Quattro Jump software). Existing descriptions of the data reduction method, (Table 2.2), demonstrate a vast variety of processes employed. Although data reduction appears to vary with test methodology, some consistencies in criteria remain. Such criteria include a set number of contacts, such as the average of all contacts recorded (Bradshaw, Le Rossignol, Williams & Lorenzen, 2006), five contacts in the middle of the trial (Hobara et al., 2008), three consecutive contacts (Ferris & Farley, 1997; McLachlan et al., 2006) an average of 10 (Granata et al., 2002b) or an average

Table 2.2

Varied Stiffness Equations and Data Reduction Methods within the Literature Assessing Continuous Double-Leg Repeat Jump Tasks.

Authors	General Topic Area	Participants	Contacts	Jumping Pace	Data Reduction Method	Equation
Bradshaw et al. (2006)	Field measures of talent-selected gymnasts	20 ♀ gymnasts (8-14 yrs)	5	Self-selected	5 contact average	$\frac{Fi}{COM\ disp}$
Bishop et al. (2006)	Effect of footwear type on stiffness in dynamic activities	9 'healthy' (age: 28.0 ± 6.8 yrs)	1 min (x3)	2.2 Hz	Contacts within 5% of frequency	$\frac{Fmax}{COM\ disp}$
Dalleau et al. (2004)	Validity of contact mat stiffness calculations	7 ♂, 1 ♀ (age: 33.0 ± 10.0 yrs)	10s	1.8 – 4.0 Hz (0.2 Hz intervals)	Average of all contacts	$\frac{Fmax}{COM\ disp}$
Farley et al. (1998)	Leg stiffness adjustment on different surfaces during jumping	3 ♂, 4 ♀ 'healthy' (age: 24.4 ± 5.0 yrs)	10s	2.2 Hz	3 consecutive contacts within 2% of frequency	$\frac{Fi}{COM\ disp}$
Farley & Morgenroth (1999)	Ankle stiffness influence on leg stiffness in jumping	3 ♂, 2 ♀ 'healthy' (age: 20-23 yrs)	NS	2.2 Hz	Contacts within 2% of frequency	$\frac{Fmax}{COM\ disp}$
Fiolkowski et al. (2005)	Plantar feedback stiffness regulation	9 ♂, 1 ♀ students (age: 28.0 ± 6.8 yrs)	30s	2.2 Hz	15 contacts within 5% of frequency from middle of trial	$\frac{Fmax}{COM\ disp}$
Granata et al. (2002)	Gender difference in leg stiffness	Study 1: 15 ♂ (age: 32.1 ± 8.3 yrs) 15 ♀ (age: 32.6 ± 9.7 yrs) Study 2: 11 ♂ (age: 27.8 ± 4.3 yrs) 10 ♀ (age: 24.1 ± 4.3 yrs)	30 (approx.)	Study 1: Self-selected, 2.5 Hz & 3.0 Hz Study 2: Self-selected & 3.0 Hz	10 contact average within 5% of frequency (mean value for self-selected) & force-displacement regression value of >0.80	Regression slope
Hobara et al. (2008)	Leg stiffness in endurance and power trained athletes	7 distance (20.0 ± 1.2 yrs) 7 power (20.1 ± 1.5 yrs)	15	1.5 Hz & 3.0 Hz	6^{th} - 10^{th} contacts	$\frac{Fi}{COM\ disp}$

Lloyd et al. (2009)	Reliability and validity of contact mat calculations	Reliability: 18 ♂ (age: 13.5 ± 0.5 yrs) Validity: 12 ♂, 8 ♀ (16.5 ± 0.5 yrs)	20 (frequency conditions) 5 (maximal jumps)	Self-selected, 2.0 Hz & 2.5 Hz	10 contacts 'closest' to desired frequency & 5 jump average (maximal jumps)	$\frac{Fmax}{COM\ disp}$
McLachlan et al. (2006)	Reliability of leg and ankle stiffness measures	♀ 'healthy' (age: 20.7 ± 3.2 yrs)	5s (following stability of frequency)	2.2 Hz & 3.2 Hz	3 consecutive jumps within 2% of frequency	$\frac{Fmax}{COM\ disp}$
Moritz & Farley (2005)	The effect of jumping on elastic surfaces	8 ♂ (age: 29 ± 6 yrs)	10s (last period of 40s)	2.2 Hz & 3.0 Hz	10 consecutive jumps closest to frequency	$\frac{Fi}{COM\ disp}$
Padua et al. (2005)	Gender differences in leg stiffness	11 ♂ 'physically active' (age: 27.8 ± 4.4 yrs) 10 ♀ 'physically active' (age: 24.1 ± 3.8 yrs)	45 (approx.)	Self-selected & 3.0 Hz	First 10 acceptable jumps within 5% frequency (mean for self-selected) & force-displacement regression >0.80	Regression slope
Racic et al. (2009)*	Stability of ground reaction force parameters	6 ♂, 6 ♀ (age: 28.6 ± 3.1 yrs)	25s	2.0 Hz, 2.4 Hz & 2.8 Hz	20 contact average in the middle of trial. Stability measure based on the first 10 contacts of this 20.	N/A
Ranavolo et al. (2008)*	Comparison of centre of mass displacement calculations during double-leg jumping	10 ♂ 'healthy' (age: 24-32 yrs)	20	1.2 Hz-3.2 Hz (0.4 Hz intervals)	6^{th}-15^{th} contact average, within 2% of target frequency	N/A

Note. NS: Not specified; N/A: Not applicable; *Fmax*: the maximum vertical force during contact; *Fi*: the instantaneous vertical force at the lowest point of the centre of mass during contact;* Used double-leg repeat jumps but didn't specifically assess leg stiffness. In the case of an author or particular group of authors who utilised the same criteria, only one representative paper has been included.

of 15 contacts (Fiolkowski, Bishop, Brunt & Williams, 2005). Additional criteria include contacts that fall within a target range of either the average self-selected frequency or the desired frequency. Generally a target range $\pm$ 2% (e.g. McLachlan et al., 2006) or $\pm$ 5% (e.g. Granata et al., 2002b) is selected, although justification for selected criteria is lacking. No authors appear to identify jump frequency exclusion on a statistical measure of intra-trial variability such as the standard deviation. Previous research has also employed a force-displacement regression slope criteria of greater than 0.80 for contact inclusion (Padua et al., 2005). Although appearing arbitrary, this criterion is based on the concept that in true spring-type behaviour, force application would never correspond to decreased centre of mass displacement (spring extension) or vice versa (Farley et al., 1991). The force-displacement regression criterion has generally been used when the force-displacement regression slope is used to represent leg stiffness. Typically a combination of these criteria is applied, and an average of the acceptable contacts, represents the lower limb stiffness of an individual. Despite a wide variety of data reduction methodology, to date no assessment of the impact of data reduction on the reliability of lower limb stiffness measures has been conducted. Additionally, despite the wide use if MSS throughout the literature, a paucity of information regarding the reliability of various stiffness methodologies, calculations and data reduction methods exists.

2.2.3 The Reliability of Musculoskeletal Stiffness Measures

Despite the widespread use and acceptance of MSS measures within the scientific literature, there is scant literature on the reliability of MSS measures. Of the limited research available, variance in test methodology, stiffness calculations and data reduction also exists making the evaluation of stiffness measures and their reliability difficult.

To the best of the author's knowledge, only two papers have directly assessed the reliability of lower limb stiffness measures during double-leg repeat jumps, McLachlan et al. (2006) found good inter-day reliability (ICC: 0.85-0.94, CV%: 2.7-5.0%) during normal jumps and jumps for maximal height at jump frequencies of 2.2 and 3.2 Hz. Lloyd, Oliver, Hughes and Williams (2009) indicated good to moderate inter-day reliability (ICC: 0.83-0.94, CV%: 9.5-13.9%) for repeat jumping at 2.0 Hz and 2.5 Hz but poor reliability (ICC: 0.74-0.89, CV%: 19.1-21.4%) for five maximal repeat jump trials in male youths. Lower limb stiffness calculations in these studies were based on the use of contact and flight times from contact mats not force plate data. As part of the same study, the authors established the validity of the contact mat method for the sub-maximal jumps at selected frequencies with force plate measures but poor validity for 5 maximal jumps. Thus, the reliability results for this condition may be questionable. To the best of the authors' knowledge, there has been no investigation into the intra-trial reliability of MSS measures during double-leg repeat jumps or the impact of data reduction on their reliability.

Whilst not directly assessing lower limb stiffness, Racic, Pavic & Brownjohn (2009) assessed the intra-trial stability of the mean value of seven variables including peak force, rate of force development and impulse during repeated double-leg jumping at a range of jump frequencies (1.4-2.8 Hz). They reported high ICC values (0.83-0.99) for both peak force, rate of force development and impulse across a range of jump frequencies (2.0, 2.4 and 2.8 Hz) with a maximum of seven contacts required to reach a mean 'stability' based on their criteria. One would assume that if the force-time curve variables exhibit intra-trial reliability then the subsequent stiffness calculations should be somewhat similar.

Particularly for high level adolescent female participants, where potential changes in strength, coordination and motor skill are occurring, the reliability of typical lower limb stiffness measures requires assessment. Undergoing such rapid changes to their physical makeup coupled with the increasing demands of training, competition and skill learning may increase the variability and inconsistency of movement within this population of athletes. Thus, in addition to the limited research available, an evaluation of reliability of stiffness measures is required for high level adolescent female athletes. The quantification of error may also provide a guide for the evaluation of what potential 'real' MSS changes across time, which is beneficial in their longitudinal assessment. Despite the wide variance in methodology, stiffness equations and data reduction methods, there have been several investigations into the underlying mechanisms of lower limb stiffness and the adjustment of stiffness during dynamic activity.

2.2.4 Mechanisms of Musculoskeletal Stiffness

Lower limb MSS can serve to both cushion the impact of ground contact and produce propulsion during takeoff. During hopping type simulations where the hip and knee joints remain relatively stable, the muscles of the lower leg extensors have been shown to act isometrically (Kawakami, Muraoka, Ito, Kanehisa, & Fukunaga, 2002). This results in the Achilles tendon storing and releasing elastic energy (Kawakami et al., 2002). It has been suggested that the primary mechanism for controlling stiffness during hopping is via the ankle joint (Farley & Morgenroth, 1999). However, conflicting research would suggest changes to knee joint stiffness are more dominant in adjusting leg stiffness during jumping tasks (Hobara et al., 2009). Further research into the mechanisms behind leg stiffness adjustment on different surfaces suggests stiffness control via adjustments at both the knee and ankle joints (Farley et al, 1998). During running, leg stiffness appears primarily controlled via knee flexion/extension with increases in running velocity coupled with increases in knee and corresponding lower limb stiffness (Arampatzis et al., 1999).

Maximising propulsive power is a key element to success in explosive sports such as gymnastics and athletics (Bradshaw & Le Rossignol, 2004; Maulder, Bradshaw, & Keogh, 2006). Faster, more explosive ground contacts, as displayed in sprinting, can be achieved by increasing leg stiffness (Kuitunen et al., 2002). Komi (2000) suggests this is via pre-impact activation levels and altered muscular recruitment patterns. When the lower limb is 'braced' in an extended position at the hip, knee and ankle, the lower limb is able to resist bending forces, such as when an athlete wants to increase the speed of motion and/or jump as high as possible. When the lower limb is more compliant, bending forces result in deformation of the leg at the hip, knee and ankle which helps to absorb forces, such as when slowing down or absorbing an impact during a safe landing.

Observations of lower limb stiffness have revealed that leg stiffness is adjusted to accommodate different surfaces. Leg stiffness can be adjusted up to 3.6 fold to accommodate a corresponding change in surface stiffness (Ferris & Farley, 1997). It appears leg stiffness is adjusted to ensure the overall stiffness of the system (leg plus surface) remains the same across numerous surfaces resulting in similar rebound properties. Thus COM mechanics remain essentially unchanged, irrespective of changes to surface hardness, stiffness, resilience and/or texture. Stiffness adjustment appears relatively instantaneous with research indicating changes with the initial step on a new surface (Ferris et al., 1998). Lower limb stiffness can also be adjusted through the use of verbal cues (Arampatzis et al., 2001). Associated research into landing control would suggest that these adjustments can be influenced and altered by training (Hewett, Stroupe, Nance & Noyes, 1999b). Although it would appear that MSS can be adjusted, there is limited research into the influence of sport-specific training on MSS adjustment, particularly longer-term adaptations to training.

Limited cross-sectional studies suggest greater MSS is associated with explosive, power athletes when compared with endurance athletes (Harrison et al., 2004; Hobara et al., 2008). However, an investigation in to differences in single-leg jumps for height (vertical displacement), suggested no significant MSS differences between athletes from sports with a large component of jumping (volleyball, basketball, high jump and handball; Laffaye et al., 2005). In one of the few studies to look at MSS changes with training, a 6-week plyometric training program found increases in ankle musculotendinuous stiffness using a perturbation protocol which was accompanied by improvements in running economy. In addition, 12 weeks of plyometric training showed a positive effect on jump performance and ankle joint stiffness in untrained males (Kubo et al., 2007). Although not significant, small improvements in jump performance and ankle stiffness appear evident with a weight-trained group within the same study. Although it would appear specific training adaptations have an effect on MSS and related performance, there is little research into the longitudinal changes of MSS or how these changes may be affected by sport-specific training or growth, particularly in the developing athlete.

Whether lower limb stiffness is influenced by fatigue remains unclear. Research into jumping to exhaustion indicates a reduction in leg stiffness under fatigue suggesting that the lower leg muscles play a significant role in modulating stiffness under fatigue (Kuitunen et al., 2007). In contrast, Padua et al. (2006) did not find significant changes in lower limb MSS following a fatigue protocol. Despite the lack of significance, the results indicate a trend toward increased stiffness following fatigue even with a relatively small participant number (n=21, 11 males and 10 females). In addition to this apparent trend, Padua et al. (2006) found that the muscular patterning (from EMG analysis) used to maintain stiffness was altered in a fatigued state. The fatigue effect on MSS and on the neuromuscular firing strategies used to maintain a certain level of lower limb stiffness may have implications when considering increased injury risk. Although the direction of stiffness change under fatigue is unclear, previous research would suggest that lower limb MSS and underlying neuromuscular strategies vary under different conditions (Coventry, O'Connor, Hart, Earl & Ebersole, 2006). In light of this, the ability to consciously change leg stiffness to maximize performance and/or minimize injury risk appears feasible.

Previous research suggests lower limb stiffness during gait may reflect fundamental properties of the musculoskeletal system, such as tendon and reflex properties (e.g. McMahon & Cheng, 1990). Recent research also suggests a role for plantar feedback in regulating stiffness however the exact mechanism by which this occurs still remains unknown (Fiolkowski et al., 2005). Increasing lower limb stiffness can be beneficial to performance through increased power production (Bradshaw & Le Rossignol, 2004; Bradshaw et al., 2006; Butler et al., 2003). However, increased stiffness for other movement tasks may prove detrimental. Under increased eccentric loading, as in drop jumps from increased heights, higher MSS transferred greater forces to the musculoskeletal system reducing the ability to attenuate these higher loads (Walshe & Wilson, 1997). It was suggested that higher stiffness was due to less effective use of contractile elements (e.g. tendon loading and energy return) and increased reflex induced inhibition. Thus, measures of leg stiffness may be an appropriate measure in injury prevention screening and talent identification.

It would appear a certain amount of lower limb stiffness is required for an athlete to maximize their performance through appropriate energy storage and return. A lack of MSS during the critical stages of force production may result in unwanted collapse of the limb, energy dissipation, reduced efficiency and potentially soft tissue injury. However, excessive lower limb stiffness may also place an athlete at risk of injury through increased eccentric loading of the musculoskeletal system and subsequent breakdown of tendons, their attachments and/or bone. This may be acute or overuse in nature. Indeed current research into MSS suggests it is linked to injury (Butler et al., 2003; Bradshaw et al., 2006). Thus, the same mechanisms and level of MSS that may enhance an athlete's performance may also place them at an increased risk of injury.

2.2.5 Musculoskeletal Stiffness and Injury

Despite the potential of lower limb MSS as a key parameter in relation to the way an individual deals with force during contact and subsequent injury risk, there is relatively little research directly assessing the link between MSS and injury. Of the limited research available, the majority is retrospective which provides an indication of the existence of a link between MSS and injury but is unable to clarify whether differences reflect the injury itself or previous injury potential. Despite the apparent lack of direct literature in this area, it would still appear that an association between too little or too much stiffness and increased injury incidence exists (Butler et al., 2003).

Although not directly investigating MSS, Hewett et al. (1999b) assessed the effect of a 6-week plyometric jump training program on landing kinetics and kinematics and isokinetic strength in high school female team sport athletes. Following the intervention program they found a reduction in peak landing force whilst maintaining a similar range of knee flexion. These changes in landing mechanics were coupled with increases in isokinetic strength. In a follow up study (Hewett, Lindenfield, Riccobene & Noyes, 1999a), the effect of the same 6-week jump training program on prospective injuries was investigated in a larger cohort of female high school team sport athletes. The researchers reported a decrease in recorded injuries across the sporting season within a pre-season trained group compared with a similar non-trained and control group. It was suggested the reduction in the incidence of injury within the pre-season trained group was due to improvements in technique and strength. Although not directly quantifying MSS in either study, these results would imply a potential link between MSS during landing and potential injury risk in adolescent female athletes.

Differences in both retrospective injuries and level of leg stiffness during running in high-arch and low-arch classified runners have been identified (Williams, McClay & Hamill, 2001; Williams et al., 2003). High-arch runners exhibited higher lower limb leg and knee stiffness coupled with a significantly higher history of bone related and ankle injuries. Low-arch runners exhibited less MSS and a higher previous incidence of soft tissue and knee injuries. It was suggested that increased leg and knee stiffness accompanied by the subsequent decreased knee flexion in the high-arch runners resulted in a decreased contact time and increased loading rate at contact. This increased loading resulted in a higher incidence of bone and tibial stress related injuries (Williams et al., 2001, 2003). The greater levels of knee excursion during contact in the low-arch runners was thought to be due to lower levels of leg and knee stiffness and may have contributed to a higher incidence of patella and medial knee injuries in the low-arch runners. Similarly, Granata et al. (2002a, 2002b) investigated the differences between males and females during active isometric and functional stiffness in an attempt to begin to explain the observed gender bias in musculoskeletal injury rates. They found lower levels of MSS during both knee extensor and flexor perturbations (Granata et al., 2002a) and double leg repeat jumps at 2.5 Hz, 3.0 Hz and self-paced jump frequencies (Granata et al., 2002b). The authors proposed that the decreased stiffness exhibited by females across all conditions may result in lower levels of muscular control and stability, particularly at the knee, which may place these athletes at increased risk of musculoskeletal injuries, although it is acknowledged that further research in this area is needed to establish this link.

A recent retrospective study into the link between lower limb MSS and injury in high-level gymnasts reinforces the potential link between extreme levels of stiffness and injury (Bradshaw et al., 2006). A potential ‘safe-zone’ of lower limb MSS was indentified with gymnasts who displayed high levels of MSS during a straight-leg repeat jump tasks indicating a previous a landing related ankle injury. In contrast, gymnasts who displayed low levels of MSS within the same task had experienced a previous ankle injury sustained during take-off (Figure 2.6).

Although these findings support the relationship of increased injury risk and different levels of MSS, variation in MSS may in fact represent physical adjustments to impact loading due to the nature of the injuries themselves, not in fact the differing levels of MSS placing the gymnasts at increased injury risk. The need for prospective, longitudinal investigations into MSS and injury risk is apparent to clarify this potential relationship within athletic populations. In the only study to prospectively

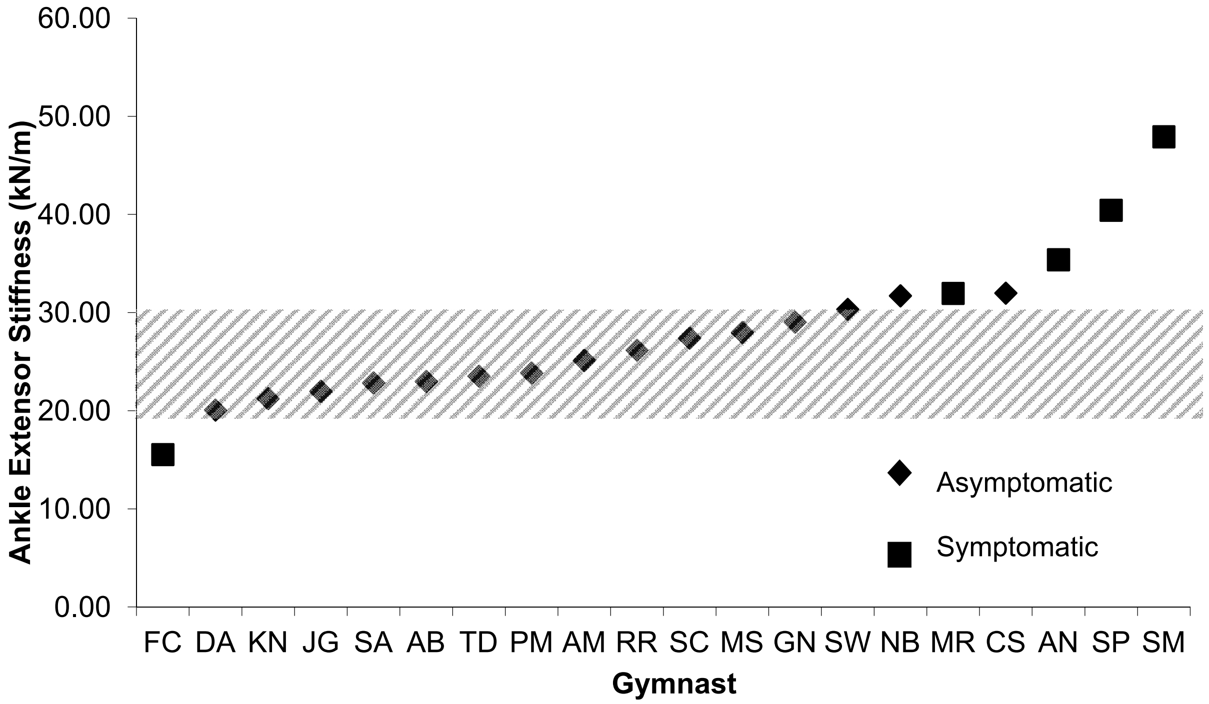

Figure 2.6 Lower limb MSS during a straight-leg repeat jump task and retrospective injury in high-level gymnasts. (Source: Bradshaw et al., 2006)

investigate stiffness measures with injury, a recent study into Australian Rules Footballers indicated a possible link between increased hamstring and leg stiffness and hamstring strain (Watsford et al., 2010). Interestingly within those injured players, the injured leg displayed decreased levels of stiffness relative to the uninjured side. Results from this study may be somewhat limited due to a relatively small proportion of injuries with the study group.

Although longitudinal, prospective research is needed to clarify the links between ‘optimal’ levels of MSS and injury risk; it would appear that too much stiffness during ground contact increases the loading on the bones and joints which potentially places an athlete at increased risk of stress related injury. Conversely, too little stiffness may result in greater range of motion and decreased stability at the joints, placing an athlete at risk of soft tissue or joint ligamentous injury. Thus, by longitudinally profiling the musculoskeletal health, anthropometry, training load and lower extremity stiffness characteristics of four distinct populations of adolescent females over a 12 month period, the impact of growth, sport-specific training and MSS on performance and injury risk can be investigated.

2.3 Study Aims

The purpose of this study was to investigate the link between lower limb MSS and injury risk in high level adolescent female athletes in high-impact and high training load sporting populations. This was achieved by longitudinally profiling markers of musculoskeletal health, anthropometry, training load, lower extremity MSS characteristics and injuries over a 12 month period.

The specific aims of the study included;

1. To investigate the impact of the data reduction method on a typical measure of MSS (Chapter 4),
2. To investigate the intra and inter-day reliability of different musculoskeletal measures within an adolescent female population (Chapter 5),
3. To investigate potential differences in lower limb MSS between high-impact (gymnastics and track and field), low-impact (water polo) and non-sporting (controls) populations (Chapters 6 & 7),
4. To investigate the relationship between lower limb MSS and the prevalence of injury, particularly specific overuse and 'stress' related type injuries (i.e. stress reaction, stress fractures, shin splints etc.) in high-impact, high training load adolescent female athletes (Chapter 8), and

5. The development of a potential multi-factorial model to predict injury risk in high level adolescent female athletes (Chapter 8).

CHAPTER THREE

General Methods

The specific experimental chapters contained in this thesis have been designed as somewhat ‘stand-alone’ papers and as such contain a methods section outlining the details of specific test procedures relevant to that particular section. However this chapter presents a general overview of some of the generic elements pertaining to the overall research project, including the research design, participant recruitment and general test methodology.

3.1 Research Design

The main research study (Study Two, see Figure 3.1) design principally involved a prospective, observational cohort design. Although each participant group was only tested across a twelve month period, data collection spanned approximately twenty-two months. Reliability testing was conducted in September 2007. Baseline testing began in December 2007 assessing both gymnasts and track and field athletes with the final data collection session conducted with water polo players in October 2009. For the three sporting groups, the test sessions were planned to coincide with what was considered a major national competition for the year. Track and field testing occurred just following the National Under Age championships, gymnastics testing coincided with the National Clubs competition, and water polo testing was conducted just following the National Under Age championships. The majority of non-sporting participant test sessions coincided with the end of the school year with some additional participants tested in the middle of the year to adequately age-match the sporting groups.

This research investigated whole-body kinetics, injury and jump performance in adolescent females (aged 12 to 18 years). Initially, a reliability study was conducted to assess the most appropriate method of processing the data (data reduction) and to establish the reliability of the test protocols to be used in the main study within an adolescent female population. The major study longitudinally tracked musculoskeletal stiffness and injury within the four sub-groups of adolescent females. In addition, surveys were conducted at baseline testing to identify other possible contributing factors to prospective injury. An overview of the general research design and corresponding thesis chapters is contained in Figure 3.1.

3.2 Ethics Approval

Prior to research commencement, ethics approval was obtained from the Human Research Ethics Committee (HREC) at the Australian Catholic University (Appendix A).

3.3 Participant Recruitment

Participants were recruited using two recruitment processes. Sixteen adolescent females were recruited for the reliability study. A further one hundred and thirteen participants were recruited at the time of baseline testing. From this initial group, eighty-three participants completed both baseline and follow-up testing at 12

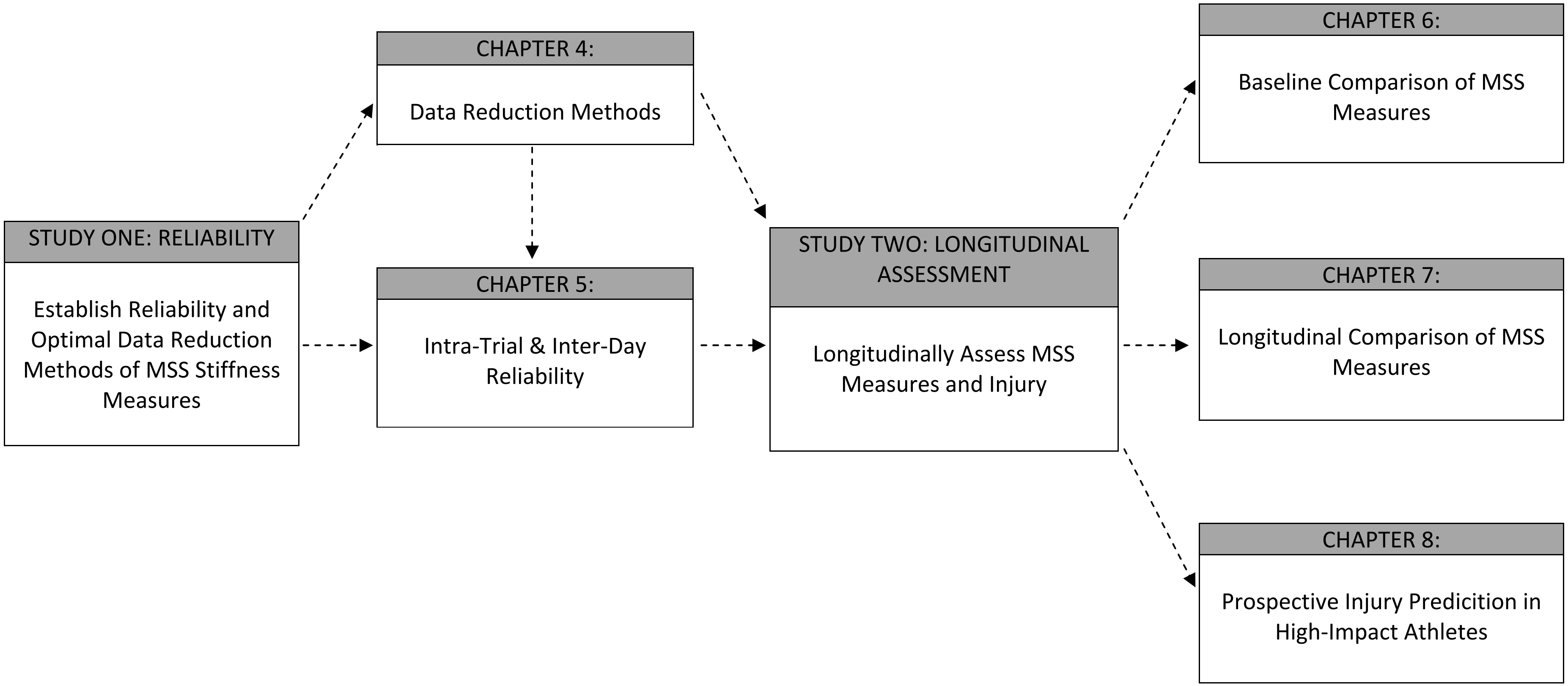

Figure 3.1. Overview of research design and related thesis chapters.

months. Specific details regarding participant numbers and descriptive data for each sub-population are tabled with the relevant thesis chapters.

The participants formed a sample of convenience. Athletes were recruited predominantly through coaches and squads associated with the New South Wales (NSW) Institute of Sport. Track and field athletes were recruited from the Emerging Athlete Program junior development squad. Water polo players were mainly recruited from the NSW U17 and NSW Institute of Sport water polo squads. Gymnasts were recruited through key coaches connected with the Queensland Academy of Sport, Australian Institute of Sport and Methodist Ladies College High Performance gymnastics programs. Non-sporting participants were recruited through the physical education department at Santa Sabina College, Sydney, Australia. In compliance with Ethics Guidelines participants who volunteered for the study were free to withdraw at any time. The information letter provided to participants and parents of participants are contained in Appendix B. Participant and parental/guardian consent for participants under 18 years of age was obtained prior to participation in the study.

3.3.1 General Inclusion Criteria

- Females aged between 12 and 18 years at the commencement of the study.
- Injury free at the commencement of baseline testing. The criteria for injury was when a volunteer had not participated in training for more than seven days and/or had not participated in two sequential competitions at the time of testing (Noyes, Lindenfeld & Marshall, 1988).
- Non-sporting participants were defined as those participating in less than four hours of organized sporting activity per week outside of normal school requirements.

3.4 General Test Procedures

3.4.1 General Test Protocol

The participants performed a self-administered warm-up prior to the testing session. Warm-ups typically involved approximately 5 minutes of whole-body exercise (e.g. jog, pedalling on an exercise bike) followed by static and dynamic stretching. Participants then completed a series of jump tasks designed to assess lower limb MSS differences. This included fifteen continuous contacts of a bent leg (CJb) and straight-leg (CJs) double-leg repeat jump task at a self-selected jump frequency (Figure 3.2). In addition, the water polo, gymnastics and track and field athletes completed 30 seconds of repeat bent-leg jumps (CJb30) designed to assess the effect of fatigue on MSS measures. Thirty seconds has been used previously as a measure of anaerobic power and leg endurance in gymnasts (Bradshaw & Le Rossignol, 2004; Jemni, Sands, Friemel, Stone & Cooke, 2006). Pilot testing also suggested that 30 seconds of jumping provided a good balance between fatigue and task demands for high-impact and low-impact sporting groups.

Non-sporting controls did not complete the fatigue task due to concerns over potential injury risk due to the increased demands of the CJb30. A self-selected jump frequency was chosen to enable lower limb musculoskeletal stiffness (MSS) assessment where participants are able to self-regulate their chosen MSS and jump frequency (Padua et al., 2005).

(a) CJb & CJb30

(b) CJs

Figure 3.2 Repeat jump tasks; a) bent-leg repeat jumps (CJb & CJb30), b) 'straight-leg' repeat jumps (CJs).

For testing in study two (longitudinal analysis), site specific markers of bone health and a series of self-report surveys were also conducted. Baseline self-report surveys assessed retrospective injury, maturational and menstrual status, dietary and training hours information. Participants could either complete the surveys at the conclusion of the test session or return the information in a provided reply-paid envelope. Surveys regarding prospective injury incidence were conducted at 6 months and 12 months post-baseline. Information regarding injuries sustained in the previous 6 month period were obtained on both occasions.

3.4.2 General Test Measures

3.4.2.1 Musculoskeletal Stiffness Measures

All jumps were performed on two portable, tri-axial force plates (Kistler, 9286A, Switzerland) placed side by side that were covered with Mondo track surface to reduce slippage and mimic a typical sports surface. Due to the raised profile of the force plates, safety mats were placed around the edge of the plate in order to surround the plates and allow a small gap (approximately 5mm) to avoid interfering with force readings. Both plates were checked across a range of expected force values (49 to 5886 N – 5 to 600 kg) prior to data collection and were found to be accurate (r^2 = 1.00, P<0.01; Appendix C). The force plates were placed on a hard, flat surface (concrete) for testing. Prior to each test session, the plates were levelled using a spirit level and a three point check of vertical ground reaction forces conducted to ensure accurate force readings. The force plates and mats were fixed with double-sided tape to prevent any potential slippage.

Jumps were performed with one foot placed on each of the two force plates. Ground reaction forces (1000 Hz) were filtered with a dual, low-pass Butterworth filter (cut-off frequency: 100 Hz) using the Bioware software (Kistler, Switzerland; Racic et al., 2009). Force-time data were then exported and analysed using a custom spreadsheet (Microsoft Office Excel 2007, Microsoft Corporation). Force data from both plates were summed to represent the force applied to the body's centre of mass. A force threshold of 10 N was used to indicate plate contact (Stalbom, Holm, Cronin & Keogh, 2007). Centre of mass displacement was calculated through the double integration of the vertical acceleration, obtained by dividing the vertical ground reaction force by the participant's mass (Cavagna, 1975). The double-integration method of calculating centre of mass displacement has validity (Ranavolo et al., 2008). The specific measures of MSS used for each study are outlined in each chapter but consisted of a ratio of force divided by centre of mass displacement in the relevant phase of contact (i.e. eccentric or concentric). Variables including peak force, centre of mass displacement, jump height and the force-displacement regression during the eccentric phase were calculated for each contact of each trial.

The first and last contacts from each trial of CJb and CJs trials were removed as being atypical based on initial data analysis and observation during testing. The remaining contacts were then reduced using specific criteria of inclusion. In the reliability study, this incorporated a wide variety of measures based on specific criteria from previous literature including jump frequency, contact time, force-displacement regression values and a defined number of contacts (i.e. the middle five contacts only). Data reduction for study two was based on the most suitable method established in the reliability study.

For the CJb30 jump tasks, MSS measures for the first ten contacts (CJb30Early) and the last ten contacts (CJb30Late) were calculated as separate values to assess any potential effects of fatigue on stiffness reliability. Data reduction was conducted as per the CJb and CJs tasks as outlined above. Following data reduction, the stiffness values of the remaining contacts were averaged for each individual for subsequent statistical analysis.

3.4.2.2 Anthropometric Measures

Anthropometric measures of height and body mass were obtained for descriptive purposes. All measures were taken in accordance with the International Society for the Advancement of Kinanthropometry guidelines (ISAK, 2001) by a level 1 accredited ISAK anthropometrist. Standing height was measured using a portable stadiometer accurate to the nearest 0.5 cm (Wedderburn UW150, Sydney, Australia) and body mass was taken using portable digital scales accurate to 500 g (Wedderburn UW150, Sydney, Australia).

3.4.2.3 Site Specific Markers of Bone Health

Site specific markers of bone health were obtained using peripheral quantitative computed tomography (pQCT; XCT 2000, Stratec Medizintechnik, Pforzheim, Germany). Participants were seated with their non-dominant tibia placed in the scanner and secured so that movement of the limb was prevented. Participants were instructed to remain as still as possible during the scan. Scans were performed at the 4% and 66% tibia as measured from the anatomic reference line (cortical end plate). Tibial length (mm) was measured externally from the mid-point of the distal medial malleolus to the proximal medial tibial plateau. Trabecular area (mm^2), density (mg/mm^3) and strength strain index (SSI; mm^3) were calculated at the 4% distal tibial site using the standard pQCT software. Corticol bone area, density, SSI and muscle and fat area (mm^2) were calculated at the 66% distal tibial site. The precision of repeat measurements within our department for this equipment is 0.8% to 2.9% for the tibia.

3.4.2.4 Prospective and Retrospective Injury

Retrospective injury was assessed for the preceding two years prior to baseline testing using a self-report survey (Appendix D). An injury was defined as any physical problem as a direct result of participation in their chosen sport or activity, resulting in an athlete missing or modifying a subsequent training session or competition due to the injury (Kirialanis et al., 2003). Information on the type of injury, injury site, approximate injury date, any resulting treatment and the impact on training was gathered. Injuries reported that were not directly related to the participants' sport were excluded. Only lower body injuries were included in injury prediction analysis. Lower limb injuries were categorised based on four categories; generic lower body, acute, overuse and fracture. Acute injuries were defined as injuries having a sudden onset, whereas overuse injuries were defined by a gradual onset potentially across multiple training sessions. The fracture category included suspected fracture, stress fracture, stress reaction and suspected stress reaction.

Prospective injury was recorded at six monthly intervals across the 12 month test period using a second self-report survey (Appendix E). Injuries were defined as per the retrospective injury analysis. Information regarding injuries that occurred in the previous 6 months was collected. Details regarding the injury type, location, diagnosis (if any), treatment, severity, injury mechanism, and injury nature (new or recurrent injury) were recorded to assist in correct injury classification (Finch, 1997). As per retrospective injury, only sport-related, lower body injuries were included for further analysis. Common chronic injury problems such as Osgood-Schlatters and Severs disease were categorised as overuse injuries (Christopher & Congeni, 2002). A sub-sample of participant injury reports (n = 26) was cross-checked with athlete coaches and parents to verify recall accuracy.

Prospective injury frequencies were summarised by injury location which included multiple injuries for any one participant. Ongoing recurrent injuries were only classified as one injury. Prospective injury data was also classified by the number of athletes who experienced that injury at some point in time within the 12 month observation period. One or more injuries of a particular category from any given athlete was recorded as one, independent of incidence (e.g. two stress fractures from the same athletes was recorded as a ‘yes’ for the fracture category for that athlete, independent of the number of injuries of that type that occurred for that particular athlete).

3.4.3.5 Dietary Intake, Pubertal Assessment and Training Hours

Participants completed a three-day food diary during two weekdays and one weekend day (Appendix F). Total caloric intake (kJ), calcium intake (mg) and macronutrient data were estimated using Foodworks™ software program (Xyris Software 2007, Version 5.0, Brisbane, Australia). Pubertal status was assessed using a self-reported assessment of Tanner stage for breast and pubic hair development (Appendix G; Duke, Litt & Gross, 1980). Menstrual status included age of menarche and number of menses in the previous 12 months. Menses was coded into three categories (Appendix H); premenarcheal, oligomenorrehic (onset of menarche within the past six months) and eumenorrehic (more than nine cycles a year; Fiesler, 2001). Finally, typical training hours per week was also recorded for comparison between groups and also to confirm the non-sporting status of the control group.

3.5 General Statistical Approach

All continuous variables were checked for normal distribution using the critical appraisal approach (Peat and Barton, 2005). Normality criteria included; less than a 10% difference between the mean and median values, double the standard deviation was less than the mean, skewness and kurtosis values were between 1.0 and -1.0, the skewness-kurtosis ratio was less than 1.96 and Shapiro-Wilk test for normality results had a significance of less than 0.05. Data were considered non-normal if the mean and median values were greater than 10%, the standard deviation was more than double the value of the mean and at least one of the other criteria was met. Non-normal data was log transformed. Descriptive data were generally presented as mean values ± the standard deviation. Estimated means from analysis of covariance were presented as estimated mean values ± the standard error of the mean.

Intra-trial measures of reliability included intraclass correlations (ICC) and coefficient of variance (CV) calculations. ICCs were calculated using a two-tailed, mixed consistency model (Shrout & Fleiss, 1979). An ICC of 1.00 indicates perfect agreement and minimal variation for the inter-day measure of interest, with an ICC less than 0.67 indicating imperfect agreement and high variability (McGraw and Wong, 1996). CV values were calculated as the mean square error (MSE) from repeated measures analysis of variance (ANOVA) of the natural log-transformed data using the formula; CV% = 100($e^{\sqrt{MSE-1}}$) (Atkinson & Nevill, 1998). This is suggested as a better measure of the error within all the individuals (Atkinson & Nevill, 1998). CV values of 10% or below are generally accepted to represent 'good' reliability (Atkinson and Nevill, 1998).In addition to ICC and CV values, inter-day reliability assessment included inter-day bias (%Bias) and Cohen's effect size (ES). Inter-day bias was calculated using the log-transformed data and represented the inter-day difference divided by the score from day one (Hopkins, 2000). Effect size (ES) was also calculated using log-transformed data and represented the average change in the mean divided by the average of the standard deviations from both test days (Hopkins, 2000).

Analysis of variance (ANOVA) with Bonferroni post-hoc analysis was used to identify differences between groups for the 'raw' stiffness values at baseline. In addition, analysis of covariance (ANCOVA) statistically accounting for differences in jump frequency and body mass was performed to investigate relative MSS group differences. Jump frequency and body mass were accounted for due to the established relationships between MSS and jump frequency (Farley et al., 1991) and body mass (Farley, Glasheen & McMahon, 1993). In addition, site specific markers of bone health were co-varied for tibial length (Greene & Naughton, 2010). Repeated measures ANVOA and ANCOVA were conducted to assess the differences between measures of MSS taken early in the CJb30 trial and measures of MSS from late in the CJb30 trial.

Longitudinal MSS assessment included measures of the percentage change and repeated measures ANCOVA. Percentage changes were calculated as the differences between the baseline and 12 month measures divided by the baseline measure multiplied by 100. In order to utilize adjusted MSS and site specific markers of bone health for prospective injury prediction, linear regression was utilized to calculate residual scores for each individual based on their relevant co-variants and participant group. Residuals were subsequently used adjust individual scores based on a ‘typical’ participant. Injury prediction was based on receiver operating characteristic (ROC) curves and logistic regression analysis. The Statistical Package for Social Sciences (SPSS) version 17.0 was used for all statistical analyses with an alpha level set at $p<0.05$.

CHAPTER FOUR

The Impact of Data Reduction on the Intra-Trial Reliability of a Typical Measure of Lower Limb Musculoskeletal Stiffness.

This chapter investigates the reliability of the measures of musculoskeletal stiffness that we aim to use in a subsequent longitudinal study on highly active and non active adolescent females. Specifically this chapter focuses on the impact of varied data reduction methods used in previous literature on the intra-trial reliability of typical measures of musculoskeletal stiffness in adolescent females.

4.1 Abstract

The impact of data reduction methods on the intra-trial reliability of measures of lower limb musculoskeletal stiffness is unknown. Sixteen adolescent female participants representing differing types of physical activity (track and field, water polo and non-sporting) performed 15 self-paced bent-knee continuous jumps (CJb) on two force plates. Leg stiffness was calculated as the ratio of the peak force and the centre of mass displacement for each contact. Using combinations of criteria based on previous literature, 83 data reduction methods were applied to the raw data. Data reduction suitability was assessed based on intra-trial reliability, the number of participants excluded and the average contacts excluded. Four data reduction methods were deemed suitable for use with adolescent female populations, with three consecutive contacts within 1 SD of the average jump frequency considered optimal. The average individual stiffness value was not greatly influenced by the data reduction method however, for a single participant, an average stiffness change of up

to 6 kN/m (30%) was observed. The impact of data reduction methods on intra-trial and inter-day measures of lower limb stiffness during self-selected and set frequency repeat jumps for other sporting and non-sporting populations requires further investigation. Data reduction methods used to evaluate measures of lower limb stiffness during repeated jumping tasks warrant consideration.

4.2 Introduction

Research into lower limb stiffness seeks to understand how an individual attenuates ground reaction forces with the body's mass by modelling the muscles, tendons and ligaments of lower leg as a simple spring (Latash & Zatsiorsky, 1993) during activities such as running (McMahon & Cheng, 1990; Farley & Gonzalez, 1996; Dalleau et al., 1998) and jumping (Walshe & Wilson, 1997). It has been suggested that the control of lower limb stiffness is important for both performance and safety (injury prevention; Butler et al., 2003). Despite its wide use in the literature, there is a paucity of literature assessing the reliability of leg stiffness measures.

Leg stiffness is most commonly evaluated during continuous (repeat) jumping tasks (e.g. McLachlan et al., 2006). Generally, a series of continuous jumps is completed on a force plate(s) at either a set (e.g. 2.5 Hz, usually controlled via the use of a metronome) or self-selected jump frequency. Through the direct measure of ground reaction forces, leg stiffness (k) can be calculated as the ratio between the peak force and centre of mass displacement during contact, based on Hooke's Law (Butler et al., 2003). Centre of mass displacement can be derived through the double integration of the acceleration-time curve (Cavagna 1975). This method requires only the use of force plate data and has been shown to be accurate during vertical jumping (Ranavolo et al., 2008).

Much of the literature has investigated musculoskeletal stiffness (MSS) using repeat jumps performed at set frequencies due to the established relationship between lower limb stiffness and jump frequency (Farley et al., 1991). The use of self-paced repeat jump tasks allows investigation into MSS under conditions where participants are able to self-regulate their lower limb stiffness and subsequent jump frequency (Padua et al., 2005). Although the use of self-paced repeat jumps may introduce potential jump frequency variation, previous literature has shown consistency in self-selected jump frequency (approximately 2.2 Hz; Farley et al., 1991). Additionally, differing jump strategies (self-selected versus maximum jump height) at the same jump frequency have identified differences in lower limb stiffness (Farley et al., 1991; Farley & Morgenroth, 1999; McLachlan et al., 2006). A relationship between ground contact time and MSS has been shown (Arampatzis et al., 2001). The use of contact time or a combination of jump frequency and contact time may be a better discriminator of potential stiffness variation. Like the diversity in leg stiffness activities assessed in the literature, variations in the stiffness calculation and data reduction methods also exist. This can present difficulties when attempting to compare present results with the literature, and also when seeking to use published normative data in athletic testing and monitoring.

Although much of the literature assessing lower limb stiffness during continuous jumps includes some detail on the method of stiffness calculation for a single contact, the data reduction process is often less transparent. Presumably this stems from the need to keep manuscripts succinct and avoid reader confusion through the use of overt detail, and/or where manufacturer software has been used (e.g. Kistler Quattro Jump software). Existing descriptions of the data reduction method, (Table 4.1), demonstrate a vast variety of processes employed. Although data reduction appears to vary with test methodology, some consistencies in criteria remain. Such criteria include a set number of contacts, such as the average of all contacts recorded (Bradshaw et al., 2006), five contacts in the middle of the trial (Hobara et al., 2008), three consecutive contacts (Ferris & Farley, 1997; McLachlan et al., 2006) or an average of 10 (Granata et al., 2002b) or 15 contacts (Fiolkowski et al., 2005). Additional criteria include contacts that fall within a target range of either the average self-selected frequency or the desired frequency. Generally a target range $\pm$ 2% (e.g. McLachlan et al., 2006) or $\pm$ 5% (e.g. Granata et al., 2002b) is selected, although justification for selected criteria is lacking. No authors appear to identify jump frequency exclusion on a statistical measure of intra-trial variability such as the standard deviation. Previous research has also employed a force-displacement regression slope criteria of greater than 0.80 for contact inclusion (Padua et al., 2005). Although the regression value appears arbitrary, this criterion is based on the notion that in true spring-type behaviour, force application would never correspond to decreased centre of mass displacement (spring extension) or vice versa (Padua et al., 2005). The force-displacement regression criterion has generally been used when the force-displacement regression slope is used to represent leg stiffness. Typically a combination of criteria is applied, and an average of the acceptable contacts, represents the lower limb stiffness of an individual. Despite a wide variety of data reduction methodology, to date no assessment of the impact of data reduction on the reliability of lower limb stiffness measures has been conducted. As there is no currently accepted ‘gold standard’ for the assessment of MSS, measures of reliability are important in establishing the best measures and data reduction techniques to be utilised.

Table 4.1

The Data Reduction Techniques Specified in the Literature that have Reported Lower Limb Musculoskeletal Stiffness during Double-Leg Jumping Tasks.

Authors	General Topic Area	Participants	Ground Contacts Assessed	Jumping Pace	Stiffness Equation	Data Reduction Method
Bradshaw et al. (2006)	Field measures of talent-selected gymnasts	20 ♀ gymnasts (8-14 yrs)	5	Self-selected	$\frac{Fi}{COM\ disp}$	5 contact average
Bishop et al. (2006)	Effect of footwear type on stiffness in dynamic activities	9 'healthy' (age: 28.0 ± 6.8 yrs)	1 min (x3)	2.2 Hz	$\frac{Fmax}{COM\ disp}$	Contacts within 5% of frequency
Dalleau et al. (2004)	Validity of contact mat stiffness calculations	7 ♂, 1 ♀ (age: 33.0 ± 10.0 yrs)	10s	1.8 – 4.0 Hz (0.2 Hz intervals)	$\frac{Fmax}{COM\ disp}$	Average of all contacts
Farley et al. (1998)	Leg stiffness adjustment on different surfaces during jumping	3 ♂, 4 ♀ 'healthy' (age: 24.4 ± 5.0 yrs)	10s	2.2 Hz	$\frac{Fi}{COM\ disp}$	3 consecutive contacts within 2% of frequency
Farley & Morgenroth (1999)	Ankle stiffness influence on leg stiffness in jumping	3 ♂, 2 ♀ 'healthy' (age: 20-23 yrs)	NS	2.2 Hz	$\frac{Fmax}{COM\ disp}$	Contacts within 2% of frequency
Fiolkowski et al. (2005)	Plantar feedback stiffness regulation	9 ♂, 1 ♀ students (age: 28.0 ± 6.8 yrs)	30s	2.2 Hz	$\frac{Fmax}{COM\ disp}$	15 contacts within 5% of frequency from middle of trial
Granata et al. (2002b)	Gender difference in leg stiffness	Study 1: 15 ♂ (age: 32.1 ± 8.3 yrs) 15 ♀ (age: 32.6 ± 9.7 yrs) Study 2: 11 ♂ (age: 27.8 ± 4.3 yrs) 10 ♀ (age: 24.1 ± 4.3 yrs)	30 (approx.)	Study 1: Self-selected, 2.5 Hz & 3.0 Hz Study 2: Self-selected & 3.0 Hz	Regression slope	10 contact average within 5% of frequency (mean value for self-selected) & force-displacement regression value of >0.80

Hobara et al. (2008)	Leg stiffness in endurance and power trained athletes	7 distance runners (20.0 ± 1.2 yrs) 7 power-trained athletes (20.1 ± 1.5 yrs)	15	1.5 Hz & 3.0 Hz	$\frac{Fi}{COM\ disp}$	6th-10th contacts
Lloyd et al. (2009)	Reliability and validity of contact mat calculations	Reliability: 18 ♂ (age: 13.5 ± 0.5 yrs) Validity: 12 ♂, 8 ♀ (16.5 ± 0.5 yrs)	20 (2.0 & 2.5 Hz) 5 (max jumps)	Self-selected, 2.0 Hz & 2.5 Hz	$\frac{Fmax}{COM\ disp}$	10 contacts 'closest' to desired frequency & 5 jump average (maximal jumps)
McLachlan et al. (2006)	Reliability of leg and ankle stiffness measures	♀ 'healthy' (age: 20.7 ± 3.2 yrs)	5s (following stable freq.)	2.2 Hz & 3.2 Hz	$\frac{Fmax}{COM\ disp}$	3 consecutive jumps within 2% of frequency
Moritz & Farley (2005)	The effect of jumping on elastic surfaces	8 ♂ (age: 29 ± 6 yrs)	10s (last period of 40s)	2.2 Hz & 3.0 Hz	$\frac{Fi}{COM\ disp}$	10 consecutive jumps closest to frequency
Padua et al. (2005)	Gender differences in leg stiffness	11 ♂ 'physically active' (age: 27.8 ± 4.4 yrs) 10 ♀ 'physically active' (age: 24.1 ± 3.8 yrs)	45 (approx.)	Self-selected & 3.0 Hz	Regression slope	First 10 acceptable jumps within 5% frequency (mean for self-selected) & force-displacement regression >0.80
Racic et al. (2009)*	Stability of ground reaction force parameters	6 ♂, 6 ♀ (age: 28.6 ± 3.1 yrs)	25s	2.0 Hz, 2.4 Hz & 2.8 Hz	N/A	20 contact average in the middle of trial. Stability measure based on the first 10 contacts of this 20.
Ranavolo et al. (2008)*	Comparison of centre of mass displacement calculations during double-leg jumping	10 ♂ 'healthy' (age:24-32 yrs)	20	1.2 Hz-3.2 Hz (0.4 Hz intervals)	N/A	6th-15th contact average, within 2% of target frequency

Note. NS: Not specified; N/A: Not applicable; *Fmax*: the maximum vertical force during contact; *Fi*: the instantaneous vertical force at the lowest point of the centre of mass during contact; * Used double-leg repeat jumps but didn't specifically assess leg stiffness. In the case of an author or particular group of authors who utilised the same criteria, only one representative paper has been included.

The purpose of this paper was to investigate the impact of data reduction technique on the lower limb stiffness value and intra-trial reliability of lower limb MSS during a self-paced, double-leg repeat jump task. It was hypothesised that the method of data reduction would have an impact on the intra-trial reliability of a typical measure of lower limb MSS.

4.3 Methods

4.3.1 Participants

Sixteen adolescent females (age: 16.1 ± 0.8 yrs, mass: 66.4 ± 7.5 kg, height: 171.0 ± 6.1 cm) from three specific activity groups (six track and field sprinters, seven water polo players and three healthy non-sporting girls) participated in the study. It was anticipated these participants would exhibit moderate levels of intra-trial variability, ideal for an investigation into the impact of data reduction on stiffness measures. Participants were injury free at the time of testing. Participant and parental/guardian consent for participants under 18 years of age was obtained prior to participation in the study. The study was approved by the University Ethics Committee.

4.3.2 Test Procedure

The participants performed a self-administered warm-up which involved approximately five minutes of general whole-body exercise (e.g. jog, pedalling on an exercise bike) followed by static and dynamic stretching. Participants then completed a series of repeat jump tasks including one trial of fifteen continuous self-paced double-leg jumps. The participants were given a demonstration of the repeat jump task and encouraged to complete as many practice trials as required to feel comfortable that they could execute the jumps correctly. In order to maintain the integrity of self-regulated jumping but still ensure repeat jumps were continuous and as consistent as possible, participants were instructed to 'jump for maximum height whilst minimizing ground contact time'. All jumps were completed with hands on hips. Practice jumps were observed by the testers to ensure correct jump execution. A static standing position of at least 2 seconds was held prior to beginning each trial to ensure the initial conditions of zero acceleration, velocity and displacement of the centre of mass for the subsequent stiffness calculations.

4.3.3 Data Collection and Analysis

The jumps were performed on two force plates (Kistler, 9286A, Switzerland) placed side by side with one foot placed on each plate. Both plates were covered with Mondo track surface to reduce slippage and mimic a typical sports surface.

Ground reaction forces (1000 Hz) were filtered with a dual, low-pass Butterworth filter (cut-off frequency: 100 Hz) using the Bioware software (Kistler, Switzerland; Racic et al., 2009). Force-time data were then exported and analysed using a custom spreadsheet (Microsoft Office Excel 2007, Microsoft Corporation). Force data from both plates was summed to represent the force applied to the body's centre of mass. A force threshold of 10 N was used to indicate plate contact (Stalbom et al., 2007). Vertical leg stiffness (k_{vert}) was calculated as the ratio of the maximum ground reaction force during contact (F_{max}) to the displacement of the body's centre of mass (COM_{disp}) from the point of contact to its maximum depth as outlined by the following equation (Butler et al., 2003);

$$Kvert = \frac{Fmax}{COMdisp}$$

Centre of mass displacement was calculated through the double integration of the vertical acceleration, obtained by dividing the vertical ground reaction force by the participant's mass (Cavagna, 1975). The double-integration method of calculating centre of mass displacement has been shown to be valid (Ranavolo et al., 2008). Vertical (leg) stiffness, contact time, flight time, jump frequency, jump height from both impulse and flight time calculations, peak force, centre of mass displacement and the force-displacement regression coefficient during the eccentric phase of contact were calculated for each contact. Figure 4.1 is a graphical representation of the key MSS related parameters collected for a 'typical' trial.

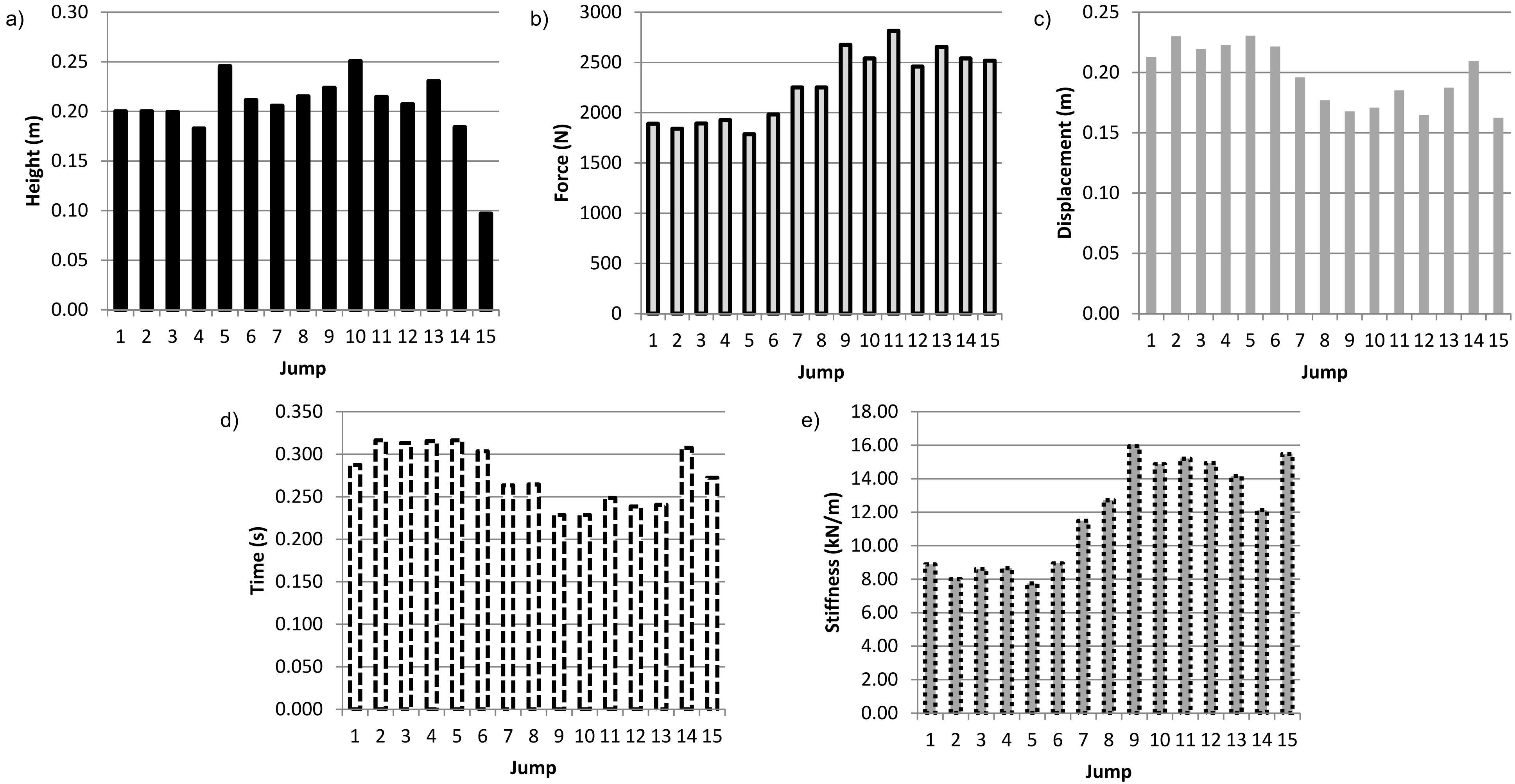

Figure 4.1 Musculoskeletal stiffness (MSS) related measures calculated for each contact during a sample trial of fifteen continuous bent-knee repeat jumps (CJb); a) jump height, b) peak force, c) centre of mass (COM) displacement, d) contact time, and e) lower limb MSS stiffness.

4.3.4 Data Reduction

Based on observation and the initial analysis of the data, the first and last contacts were removed from each trial as being atypical. An additional four contacts were removed (two contacts from one trial and one contact from two other trials) based on the peak force, a difference between the impulse and flight-time jump height calculations of greater than 0.04 m, or differences in contact time being clearly erroneous from the average jump.

A total of 83 data reduction criteria methods were then applied to the calculated data for each participant based on combinations of previously described criteria used (Table 4.2). A 'Primary' data reduction criterion was based on the number of contacts included for analysis within the trial. 'Secondary' data reduction criteria were based on jump frequency, contact time, and the force-displacement regression during the eccentric phase of the jump. An additional two specific criteria were included. Ten consecutive contacts 'closest' to the desired frequency (Moritz & Farley, 2005; Lloyd et al., 2009) was calculated as the root mean square difference from the average frequency of ten consecutive jump contacts. The first five consecutive contacts was also analysed (Bradshaw et al, 2006; Lloyd et al., 2009). Following data reduction, the stiffness values of the remaining contacts were compiled for each individual for subsequent statistical analysis. Participants with less than three jumps remaining following the data reduction criteria application were excluded. The number of excluded participants, average contacts and maximum number of contacts excluded by each criterion was recorded for subsequent data reduction technique comparison.

Table 4.2

Data Reduction Matrix Representing the Variables and Combinations of Variables used to Produce 83 Data Sets Based on Combinations of Criteria Outlined in Previous Literature.

				Secondary Data Reduction Criteria								
		r_{Fd}		Av Frequency			Av Contact Time			Av Frequency & CT		
				± 1SD	± 5%	± 2%	± 1SD	± 5%	± 2%	± 1SD	± 5%	± 2%
Primary Data Reduction Criteria	All Contacts	---	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		r_{Fd} >0.80	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Middle 10 Contacts	---	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		r_{Fd} >0.80	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Middle 5 Contacts	---	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		r_{Fd} >0.80	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	First 3 Consecutive	---	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
		r_{Fd} >0.80	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Note. Four additional data reduction methods were assessed; '10 consecutive contacts closest to the average frequency' and the 'first 5 contacts' with and without a force-displacement regression of >0.80. r_{Fd} represents the force-displacement regression coefficient during the eccentric phase of ground contact.

4.3.5 Statistical analysis

The Statistical Package for Social Sciences (SPSS) version 17.0 was used for all statistical analyses with an alpha level set at $p<0.05$. Normality of the data was checked using the critical appraisal approach (Peat & Barton, 2005). With the exception of four data reduction methods, grouped data were normally distributed and therefore parametric tests were used for statistical analyses. Non-normal data was log-transformed prior to the intra-class correlation coefficient calculation.

Means ($\overline{X}$), standard deviations (SD), intra-class correlation coefficients (ICC), and coefficient of variations (CV) were calculated for the data sets produced by each of the data reduction criteria. ICCs were calculated using a two-tailed mixed consistency model (ICC(3,k), Shrout & Fleiss, 1979). Because an individual's lower limb stiffness is represented by the average across all included contacts, the average measure ICC value was reported. An ICC of 1.00 indicates perfect agreement and minimal variation for the inter-day measure of interest, with an ICC less than 0.67 indicating that there is not absolute agreement and higher variability (McGraw and Wong, 1996). CVs were calculated using the mean square error (MSE) from repeated measures analysis of variance (ANOVA) of the natural log transformed data using the formula; CV% = $100(e\sqrt{}^{\,MSE-1})$ (Atkinson & Nevill, 1998). This is suggested as a better measure of the error within all the individuals (Atkinson & Nevill, 1998). CV values of 10% or below are generally accepted to represent 'good' reliability (Atkinson and Nevill, 1998).

Data reduction criteria that resulted in an ICC of greater than 0.90 and a CV% of less than 10% were deemed reliable (Atkinson & Nevill, 1998). Data reduction techniques that displayed ICC values of greater than 0.90 with a CV% value of between 10 and 11% were considered 'borderline' in terms of reliability. For results with an ICC of less than 0.90 and a CV% of greater than 11% the data reduction method was deemed less reliable. Additionally, the number of participants and average contacts excluded was considered important in deciding on the best leg stiffness data reduction technique. Any technique that excluded less than approximately 10% of the participants (two participants or less) or included an average of more than half of the total expected contacts per trial was considered ‘legitimate’. A data reduction method that met the criteria outlined for both the ‘reliablity’ and ‘legitimatacy’ assessments was considered a ‘suitable’ method of data reduction.

For each individual, the difference between the mean stiffness value of the un-reduced (raw) data and the mean stiffness value following each data reduction method was calculated. The average difference and range of the change in mean scores across the group was subsequently calculated.

4.4 Results

A summary of the mean and standard deviation leg stiffness values, reliability measures, participant exclusions, contact exclusions and data reduction suitability are contained in Tables 4.3 and 4.4. The results for the ‘All Contacts’ and ’Middle 10 Contacts’ conditions were almost identical, so only the ‘All Contacts’ condition has been reported.

ICC analysis revealed excellent reliability across all data reduction techniques (ICC (3,k) = 0.94-0.99). CV% results indicated reliability results ranging from a maximum value of 16.6% (average of first 5 contacts; see Table 4.3) to a minimum of 6.5% (within 2% of average contact time, r>0.80, all contacts; see Table 4.4). A number of variables indicated good CV% reliability (<10%) but excluded either greater than two participants, or more than half the overall number of contacts.

Based on the reliability and legitimacy results, four data reduction methods were deemed suitable for the present population. Specifically, acceptable reduction methods were; three consecutive contacts within 1SD of the average frequency (ICC(3,k) = 0.97, CV = 9.4%), all contacts within 5% of the average contact time (ICC(3,k) = 0.98, CV = 9.5%), the middle five contacts within 5% of the average contact time and all contacts within 1 SD of the average contact time with a force-displacement regression of >0.80 (ICC(3,k) = 0.97, CV = 9.9%). Subsequent analysis into the reliability and legitimacy of the four suitable data reduction techniques within each sub-population revealed three consecutive contacts within 1 SD of the average frequency as the preferred technique across all sub-populations (Table 4.5).

The average change in mean stiffness value due to the data reduction method remained within approximately ± 1.5 kN/m (± 9%) irrespective of data reduction method employed (Figure 4.2). The use of contact time and three consecutive contact criteria resulted in lower (conservative) mean stiffness values across participants. The use of three consecutive contacts with a frequency within either 1 SD or 5% resulted in a larger range of mean stiffness value change scores (Figure 4.2).

Table 4.3

Mean and Standard Deviation Stiffness (k) Values (mean ± sd), Reliability Statistics and Exclusion Details for Data Reduction Techniques Based on Combinations of Contacts, Frequency and Contact Time.

Data Reduction Method	k (kN/m)	ICC	CV (%)	n excl.	Av. excl.	Max. excl.	Reliable	Legitimate	Suitable
All Contacts	17.28 ± 6.02	0.98	16.2	0	0	0	No	Yes	
Middle 10 Contacts	17.27 ± 6.03	0.98	15.9	0	0	0	No	Yes	
10 Consecutive Contacts Closest to Average Frequency	17.17 ± 5.68	0.98	15.4	0	0	0	No	Yes	
Middle 5 Contacts	17.28 ± 5.96	0.96	15.0	0	0	0	No	Yes	
First 5 Contacts	16.48 ± 6.27	0.96	16.6	0	0	0	No	Yes	
Within 1SD of Average Frequency									
- All Contacts	17.31 ± 6.01	0.97	14.7	0	4	6	No	Yes	
- Middle 5 Contacts	17.39 ± 5.91	0.96	15.3	0	0	1	No	Yes	
- 3 Consecutive Contacts	16.80 ± 5.80	0.98	9.4	2	0	0	Yes	Yes	Yes
Within 1SD of Average Contact Time									
- All Contacts	17.04 ± 5.71	0.98	12.2	0	4	6	No	Yes	
- Middle 5 Contacts	16.94 ± 5.58	0.97	13.6	0	0	1	No	Yes	
- 3 Consecutive Contacts	16.91 ± 5.74	0.93	14.1	1	0	0	No	Yes	
Within 1SD of Average Frequency and Contact Time									
- All Contacts	16.91 ± 5.48	0.95	12.7	0	6	9	No	Yes	
- Middle 5 Contacts	16.48 ± 5.29	0.94	14.7	1	1	2	No	Yes	
- 3 Consecutive Contacts	16.14 ± 5.21	0.96	10.6	4	0	0	Borderline	No	
Within 5% of Average Frequency									
- All Contacts	17.23 ± 5.94	0.97	14.3	0	2	7	No	Yes	

- Middle 5 Contacts	17.39 ± 5.97	0.95	14.2	0	0	1	No	Yes	
- 3 Consecutive Contacts	16.89 ± 5.94	0.97	12.0	0	0	0	No	Yes	
Within 5% of Average Contact Time									
- All Contacts	17.46 ± 5.52	0.98	9.5	1	6	10	Yes	Yes	Yes
- Middle 5 Contacts	16.89 ± 5.75	0.98	9.8	2	1	2	Yes	Yes	Yes
- 3 Consecutive Contacts	17.23 ± 4.92	0.99	8.0	8	0	0	Yes	No	
Within 5% of Average Frequency and Contact Time									
- All Contacts	17.02 ± 5.29	0.98	9.0	3	6	9	Yes	No	
- Middle 5 Contacts	16.38 ± 5.44	0.99	10.0	4	1	2	Yes	No	
- 3 Consecutive Contacts	17.23 ± 4.92	0.99	8.0	8	0	0	Yes	No	
Within 2% of Average Frequency									
- All Contacts	17.56 ± 6.00	0.95	14.3	0	7	10	No	No	
- Middle 5 Contacts	16.70 ± 5.57	0.96	15.7	4	1	2	No	No	
- 3 Consecutive Contacts	14.74 ± 4.34	0.99	10.5	10	0	0	Borderline	No	
Within 2% of Average Contact Time									
- All Contacts	17.67 ± 4.13	0.97	8.1	9	9	10	Yes	No	
- Middle 5 Contacts	20.62 ± 3.29	0.96	8.7	13	1	2	Yes	No	
- 3 Consecutive Contacts	20.63 ± 1.05	---	---	15	0	0	---	---	
Within 2% of Average Frequency and Contact Time									
- All Contacts	18.09 ± 4.61	0.99	8.3	14	10	10	Yes	No	
- Middle 5 Contacts	---	---	---	16	---	---	---	---	
- 3 Consecutive Contacts	---	---	---	16	---	---	---	---	

Note. "3 Consecutive Contacts": represents the first series of three consecutive contacts within the specified criteria; n excl.: number of participants excluded (out of 16); Av. excl.: average contacts excluded per participant; Max. excl: maximum number of contacts excluded for any one participant.

Table 4.4

Mean Stiffness (k) Values, Standard Deviation, Reliability Statistics and Exclusion Details for Data Reduction Techniques Based on Combinations of Contacts, Frequency, Contact Time and a Force-Displacement Regression Value of r>0.80.

Data Reduction Technique	k (kN/m)	ICC	CV (%)	n excl.	Av. excl.	Max. excl.	Reliable	Legitimate	Suitable
All Contacts, r>0.80	18.10 ± 5.47	0.96	15.3	2	2	8	No	Yes	
Middle 10 Contacts, r>0.80	18.14 ± 5.48	0.96	15.3	2	1	5	No	Yes	
Middle 5 Contacts, r>0.80	17.93 ± 5.55	0.95	12.6	2	0	2	No	Yes	
First 5 Contacts, r>0.80	18.61 ± 6.09	0.94	13.4	3	0	0	No	No	
Within 1SD of Average Frequency, r>0.80									
- All Contacts	18.03 ± 5.58	0.95	14.2	2	5	9	No	Yes	
- Middle 5 Contacts	18.03 ± 5.49	0.95	13.7	2	0	2	No	Yes	
- 3 Consecutive Contacts	18.71 ± 5.20	0.97	8.3	5	0	0	Yes	No	
Within 1SD of Average Contact Time, r>0.80									
- All Contacts	17.64 ± 5.24	0.97	9.9	2	5	10	Yes	Yes	Yes
- Middle 5 Contacts	18.08 ± 5.02	0.97	10.2	3	0	2	Borderline	No	
- 3 Consecutive Contacts	19.09 ± 4.83	0.88	13.5	5	0	0	No	No	
Within 1SD of Average Frequency and Contact Time, r>0.80									
- All Contacts	17.49 ± 5.10	0.95	10.0	2	8	10	Yes	No	
- Middle 5 Contacts	17.57 ± 4.67	0.94	11.4	4	1	2	No	No	
- 3 Consecutive Contacts	18.00 ± 4.62	0.93	11.0	7	0	0	No	No	
Within 5% of Average Frequency, r>0.80									
- All Contacts	17.99 ± 5.42	0.96	13.9	2	3	9	No	Yes	
- Middle 5 Contacts	18.15 ± 5.56	0.94	14.3	2	0	2	No	Yes	

- 3 Consecutive Contacts	18.31 ± 5.36	0.96	12.0	3	0	0	No	No
Within 5% of Average Contact Time, r>0.80								
- All Contacts	18.48 ± 4.78	0.98	7.9	3	7	10	Yes	No
- Middle 5 Contacts	17.95 ± 5.08	0.98	7.2	4	1	2	Yes	No
- 3 Consecutive Contacts	19.56 ± 2.80	0.95	6.7	10	0	0	Yes	No
Within 5% of Average Frequency and Contact Time, r>0.80								
- All Contacts	18.15 ± 4.47	0.99	6.8	5	7	9	Yes	No
- Middle 5 Contacts	17.48 ± 4.65	0.99	6.6	6	1	2	Yes	No
- 3 Consecutive Contacts	19.56 ± 2.80	0.99	6.6	10	0	0	Yes	No
Within 2% of Average Frequency, r>0.80								
- All Contacts	19.01 ± 5.53	0.95	13.4	3	8	10	No	No
- Middle 5 Contacts	17.53 ± 5.21	0.97	13.7	6	1	2	No	No
- 3 Consecutive Contacts	17.01 ± 3.29	0.99	9.7	12	0	0	Yes	No
Within 2% of Average Contact Time, r>0.80								
- All Contacts	18.78 ± 3.24	0.97	6.5	10	9	10	Yes	No
- Middle 5 Contacts	19.37 ± 2.86	0.96	7.3	14	1	1	Yes	No
- 3 Consecutive Contacts	20.63 ± 1.05	---	---	15	0	0	---	---
Within 2% of Average Frequency and Contact Time, r>0.80								
- All Contacts	12.92 ± 1.22	---	---	15	10	10	---	---
- Middle 5 Contacts	---	---	---	16	---	---	---	---
- 3 Consecutive Contacts	---	---	---	16	---	---	---	---

Note. "3 Consecutive Contacts": represents the first series of three consecutive contacts within the specified criteria; n excl.: number of participants excluded (out of 16); Av. excl.: average contacts excluded per participant; Max. excl: maximum number of contacts excluded for any one participant.

Table 4.5

Mean Stiffness (k) Values ± Standard Deviation, Reliability Statistics and Exclusion Details for Suitable Data Reduction Techniques by Sub-Group.

Data Reduction Technique	**k (kN/m)**	**ICC**	**CV (%)**	**n excl.**	**Av. excl.**	**Max. excl.**	**Reliable**	**Legitimate**	**Suitable**
3 Consecutive Contacts within 1SD of Average Frequency									
- Water Polo	18.34 ± 5.50	0.96	11.0	0	0	0	Borderline	Yes	Borderline
- Track and Field	14.19 ± 4.70	0.99	6.5	2	0	0	Yes	Yes	Yes
- Non-Active	16.68 ± 7.74	1.00	6.8	0	0	0	Yes	Yes	Yes
All Contacts within 5% of Average Contact Time									
- Water Polo	18.74 ± 6.91	0.98	8.4	0	5	8	Yes	Yes	Yes
- Track and Field	16.48 ± 6.32	0.97	13.0	1	6	8	No	Yes	
- Non-Active	14.68 ± 4.74	0.99	5.8	0	9	10	Yes	No	
Middle 5 Contacts within 5% of Average Contact Time									
- Water Polo	19.59 ± 5.13	0.97	7.9	0	0	1	Yes	Yes	Yes
- Track and Field	13.97 ± 5.71	0.98	14.2	2	1	2	No	Yes	
- Non-Active	14.50 ± 4.37	1.00	5.0	0	1	2	Yes	Yes	Yes
All Contacts within 1SD of Contact Time, r>0.80									
- Water Polo	19.20 ± 4.44	0.97	9.1	0	5	10	Yes	Yes	Yes
- Track and Field	17.25 ± 6.19	0.99	8.4	2	7	9	Yes	No	
- Non-Active	14.54 ± 4.48	0.98	13.1	0	4	4	No	Yes	

Note. "3 Consecutive Contacts": represents the first series of three consecutive contacts within the specified criteria; n excl.: number of participants excluded (out of 16); Av. excl.: average contacts excluded per participant; Max. excl: maximum number of contacts excluded for any one participant. Water Polo; n = 7, Track and Field, n = 6, Non-Active, n = 3.

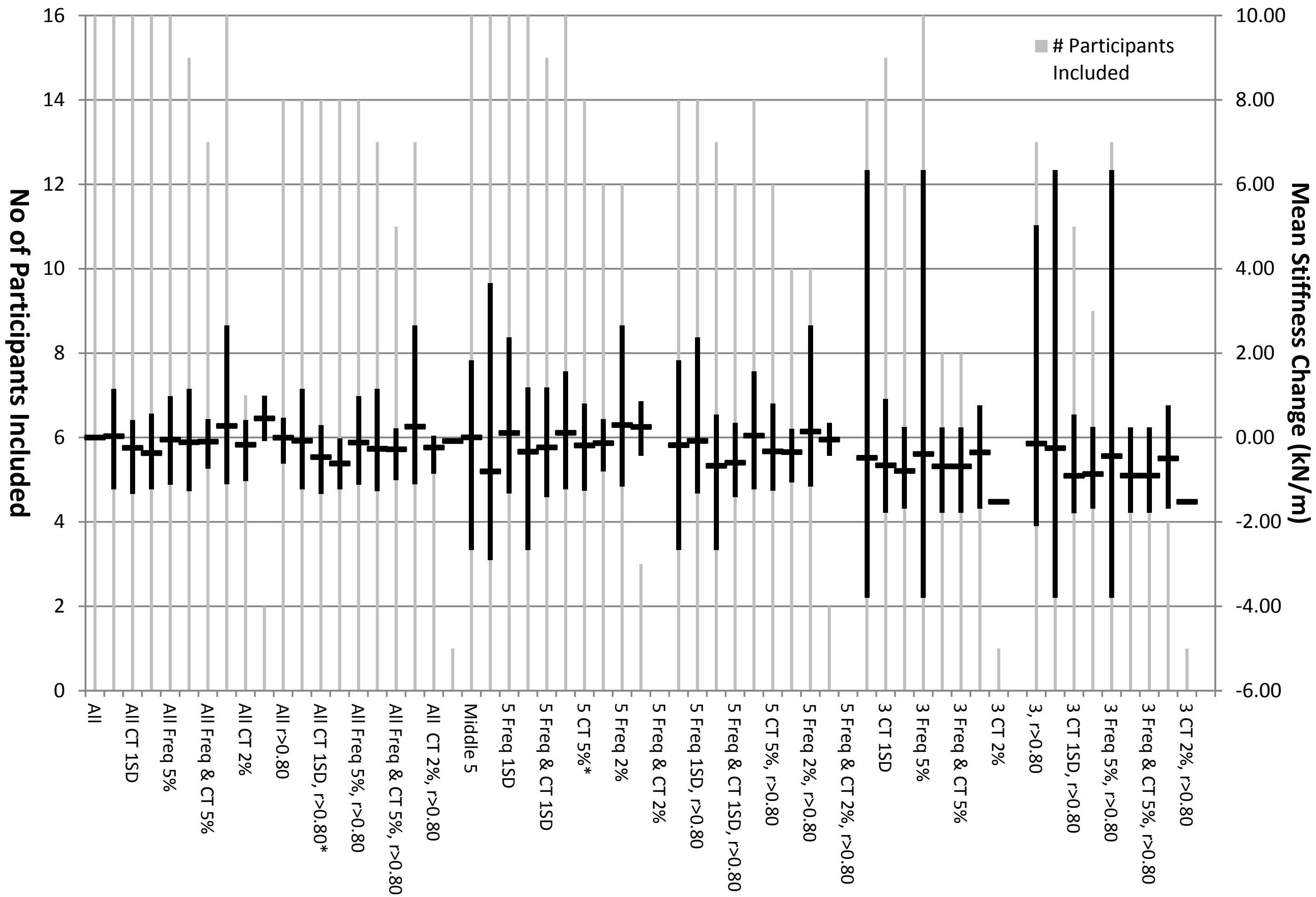

Figure 4.2 Mean and range of participant stiffness value changes due to the data reduction method from the ‘raw’ mean stiffness value.

Note. All: All contacts; Freq: jump frequency; CT: contact time; 5: middle 5 contacts; 3: 3 consecutive contacts; r>0.80: force-displacement regression greater than 0.80; 1SD: one standard deviation; * identified as suitable data reduction method.

4.5 Discussion

The findings of the present paper indicate the choice of data reduction method for a self-paced double-leg continuous jump task within adolescent females should be an important consideration. Reliability results for the ‘raw’ data indicated inherent contact-to-contact variability within the lower limb stiffness measures. Further, the use of appropriate data reduction criteria was able to achieve good intra-trial reliability whilst maintaining participant and contact inclusion. Careful consideration of the data reduction method employed is both necessary, to enable some level of confidence in the stiffness scores produced, and important, to obtain a score reflective of the ‘true’ underlying stiffness for each participant.

Adequate data reduction criteria should maintain the integrity of the data and simultaneously exclude any ‘incorrect’ or atypical jumps. Ideally, data reduction would not exclude too many contacts or participants. For self-paced continuous jumps, the use of contacts within 2 or 5% of the average contact time, 3 consecutive contacts and a force-displacement regression of greater than 0.80 were able to effectively discriminate measures of lower limb stiffness. Jump frequency as a data reduction criterion improved intra-trial reliability however it was less effective compared with the use of contacts within 2 or 5% of the average contact time in the present study. The use of consistent contact times may be a better discriminator of lower limb stiffness variation than jump frequency, despite the use of jump frequency conventionally established in the literature. Differences in lower limb stiffness with corresponding differences in contact time at the same jump frequency have been demonstrated (Farley et al., 1991; Farley & Morgenroth, 1999; McLachlan et al., 2006). Future studies may consider using contact time or a combination of contact time and jump frequency as a basis for deciding on contacts to include or exclude in statistical analysis. This might also include consideration of the specific participant repeat jump task directions, irrespective of jump frequency prescription. Although the use of three consecutive contacts or a regression constant of greater than 0.80 resulted in good intra-trial reliability, they appeared too stringent for the present population and test methodology, excluding too many participants or contacts across the majority of data reduction conditions.

Despite methodological differences, the present study indicated similar intra-trial reliability compared with the inter-day reliability reported in previous studies. Similar levels of inter-day leg stiffness reliability at jump frequencies of 2.0 and 2.5 Hz (ICC: 0.93-0.94, CV%: 7.3-17.8%) have been reported in early adolescent young males (Lloyd et al 2009). Lower limb stiffness was calculated using the average of ten contacts ‘closest’ to the desired frequency. Poor reliability for the average of five self-paced repeat jumps for maximal height was also found (ICC: 0.89, CV%: 14.7-27.6%). These results appear moderately higher than the present study however, lower limb stiffness was evaluated using contact mats with questionable validity when compared with force plate measures for maximal height jumps (Lloyd et al., 2009). Good inter-day reliability has also been reported (ICC: 0.85-0.93, CV%: 2.7-5.0%) during double-leg jumping tasks within young adult females (age: 20.7 ± 3.2 yrs) from a variety of sporting backgrounds performing jumps at 2.2 and 3.2 Hz (McLachlan et al. 2006). Data were reduced based on three consecutive contacts within 2% of the target frequency. The present study found ‘borderline’ reliability with this data reduction method. However, it appears too stringent for self-paced jumping in adolescent female athletes and non-athletes, excluding the majority of participants. Although previous research reports inter-day reliability, measures of good inter-day reliability would imply stability of scores and thus good intra-trial reliability. Future investigation into inter-day reliability using the suitable data reduction criteria identified in the present study would provide important additional information on the optimal lower limb stiffness data reduction method for self-paced continuous jumps.

The assumption in the present paper is that good intra-trial reliability reflects a data reduction method that more accurately depicts the underlying stiffness value of an individual. However, small mean lower limb stiffness differences from the ‘raw’ values were found across data reduction methods in the present paper. This may suggest the choice of data reduction does not highly influence the average stiffness value and as such may not be critical. However, reductions in intra-trial reliability may improve the sensitivity of the measures. With reduced intra-trial variability, significant differences between mean values may be more likely. This may also assist with the smaller sample sizes typical of applied research. Despite small changes to mean stiffness for the group, individual mean stiffness changes of up to 6 kN/m (approximately 30% change) were observed. Individual leg stiffness changes of this magnitude may indeed be important and as such, the data reduction method employed is worthy of consideration. An assessment of the data reduction method on the inter-day reliability for similar measures of lower limb stiffness would add more confidence to inferences on the impact of data reduction and identification of the most suitable criteria.

4.6 Conclusion

The present study would suggest that with the appropriate data reduction method applied, typical measures of MSS in adolescent females show adequate levels of intra-trial reliability. However, the specific method of data reduction has an influence on the intra-trial reliability of typical measures of MSS in adolescent females and warrants consideration. Four main methods of data reduction were identified as most appropriate. Although three consecutive contacts within one standard deviation of the mean data reduction method appears slightly superior when considering participant groups differences, consideration of inter-day reliability is required to establish the most appropriate data reduction method for this population.

CHAPTER FIVE

The Intra-Trial and Inter-Day Reliability of Lower Limb Musculoskeletal Stiffness Measures in Adolescent Females.

This chapter forms the second part of the processes undertaken within the thesis to establish the reliability of the measures of musculoskeletal stiffness used to subsequently investigate differences between highly active and non active adolescent females. Specifically this chapter focuses on the intra-trial and inter-day reliability of musculoskeletal stiffness measures across a range of repeat jump tests and stiffness calculations used in later chapters.

5.1 Abstract

Measures of lower limb musculoskeletal stiffness are widely used in the literature to quantify the collective interaction of the muscles, ligaments and tendons of the leg with the ground during contact. Despite frequent use, a paucity of literature supports the reliability of typical stiffness measures. Sixteen adolescent females from three sub-populations (track and field, water polo and non-sporting) completed two repeat test sessions. Measures of vertical stiffness from three self-paced repeat jump tasks were derived. Intra-trial and inter-day reliability measures were calculated for four data reduction techniques and five stiffness calculations. Percentage change in the mean (bias%), intraclass correlation coefficients (ICCs), coefficients of variation (CV%), and effect size (ES) were determined in evaluating the reliability and suitability of each test variation. Results indicated musculoskeletal stiffness values

during self-paced repeat jumps in the adolescent females generally show acceptable intra-trial and inter-day reliability. However, the data reduction method and stiffness calculation employed can influence reliability measures and should be considered. Future research into the impact of data reduction and stiffness calculations on intra-trial and inter-day reliability in similar and set frequency repeat jump tasks within other populations would be beneficial.

5.2 Introduction

The mass-spring model has been used to quantify the interaction between the musculoskeletal system and the ground during contact. By modelling the joints, muscles, tendons and ligaments as a single spring that attenuates the body's centre of mass with applied external forces, one can assess the compliance or stiffness of this 'spring' (Latash & Zatsiorsky, 1993). Investigations into the influence of lower limb musculoskeletal stiffness (MSS) on several performance parameters include jump height (Walshe & Wilson, 1997), running velocity (McMahon & Cheng, 1990), stride length (McMahon et al., 1987; Derrick et al., 2000), stride frequency (Farley & Gonzalez, 1996) and running economy (Dalleau et al., 1998). Lower limb stiffness measures have also been linked with injury risk (Butler et al., 2003; Brughelli & Cronin, 2006). Despite its wide use in the literature, there is limited research assessing the reliability of lower limb stiffness. Furthermore, a wide variety of test methodologies and stiffness calculations exist making the comparison of lower limb stiffness measures a challenge.

Although diversity of test methodology exists in the current literature, one of the most commonly used tasks to evaluate lower limb stiffness are double-leg repeat jumps (sometimes termed 'double-leg hopping' or 'bi-lateral hopping'). Jumps are typically completed at a set jump frequency (such as 2.2 Hz) due to established links between jump frequency and lower limb stiffness (Farley et al., 1991). However, double-leg repeat jumps using self-selected jump frequency may produce values more representative of the 'typical' stiffness and have shown repeatable jump frequencies between trials (Padua et al., 2005). It has been postulated that leg stiffness during hopping is primarily controlled by changes in ankle stiffness (Farley & Morgenroth, 1999). Subsequently, in addition to double-leg repeat jumps (CJb), repeat jump tasks with straight legs (CJs) that are designed to assess predominantly ankle joint stiffness differences, have been used to identify leg stiffness in gymnasts (Bradshaw et al., 2006). The same study also used repeat jumps over a more extended time period (30 seconds) to assess the effect of fatigue on leg stiffness. Although the foundation of lower limb stiffness is the same, inconsistencies in stiffness calculations also exist.

The most common method of calculating lower limb stiffness during repeat jump tasks is a direct transformation of Hooke's law in which a ratio of the peak force to the centre of mass displacement during the eccentric phase of the jump is calculated (Butler et al., 2003). Centre of mass displacement can be derived via the double-integration of the force-time curve generated during ground contact (Cavagna, 1975). This method of calculation requires only one piece of equipment and has been shown to be accurate for vertical repeat jumps (Ranavolo et al., 2008). The force at the eccentric-concentric transition (Fi) may be representative of the magnitude of stored elastic energy in the muscles during eccentric contraction (Bosco et al., 1982). In addition, it's suggested during running that braking stiffness (eccentric) measures may in fact be different to the stiffness properties exhibited during the propulsive phase (Hunter, 2003). In true mass-spring behaviour, Fi force will be equal to the peak force and subsequent stiffness value. Thus, researchers have used these definitions of stiffness equations interchangeably (Farley & Morgenroth, 1999). In vertical jumping tasks, such as double-leg repeat jumps, vertical compression of the leg ‘spring’ and the vertical displacement are essential. Thus, measures of leg stiffness and vertical stiffness are identical (e.g. Farley & Morgenroth, 1999). Despite frequent assessment of lower limb stiffness during continuous jumps including some detail on the method of stiffness calculation for a single contact, the data reduction process across multiple contacts is less transparent.

The limited research detailing data reduction methods demonstrates a wide variety in methodology even within the same repeat jump task (refer to Chapter 4). Data reduction techniques often reflect the methodology employed and are generally based on a combination of criteria including the number of contacts used (e.g. Hobara et al., 2008), contacts within a percentage of the desired jump frequency (e.g. McLachlan et al., 2006) or average of the self-selected frequency (e.g. Padua et al., 2006), and a force-displacement regression slope of greater than 0.80 (Granata et al., 2002b). However, little is known about how variation within existing data reduction methods may affect the stiffness measures obtained. It is possible that the method of data reduction employed has an impact on intra-trial reliability and thus warrants consideration (refer to Chapter 4). Existing leg stiffness research is limited by the absence of the intra-trial or inter-day reliability of measures of lower limb MSS, even within the more common stiffness measures such as double-leg repeat jump tasks.

Favourable inter-day reliability (ICC: 0.85-0.94, CV%: 2.7-5.0%) during normal and maximal height double-leg repeat jumps (frequencies of 2.2 and 3.2 Hz) was reported by McLachlan et al. (2006). Although intra-trial reliability was not reported, good inter-day reliability would imply some level of intra-trial reliability. Borderline inter-day reliability (ICC: 0.83-0.94, CV%: 9.5-13.9%) has also been reported for repeat jumps at 2.0 Hz and 2.5 Hz in male adolescents (Lloyd et al., 2009). However, poor reliability (ICC: 0.74-0.89, CV%: 19.1-21.4%) for five maximal self-paced repeat jump trials was also found within the same population (Lloyd et al., 2009). Lower limb stiffness calculations were based on contact and flight times from contact mats that displayed poor validity compared with force plate measures for the maximal jump test (Lloyd et al., 2009). Thus, the reliability results outlined for maximal self-paced jumps from this paper should be considered with some caution. The previous chapter (Chapter 4) investigated the impact of data reduction methods on the intra-trial reliability of self-paced repeat jumps in adolescent females. Poor to borderline intra-trial reliability was identified within the 'raw' stiffness measures. However, good levels of intra-trial reliability (ICC: 0.98, CV%: 9.4) were established when using the most appropriate criteria identified for data reduction. Although not directly assessing lower limb stiffness, the intra-trial stability of the mean value of seven variables including peak force, rate of force development and impulse during repeated double-leg jumping across a range of jump frequencies (1.4-2.8 Hz) was investigated (Racic et al., 2009). High ICC values (0.83-0.99) for peak force, rate of force development and impulse across a range of jump frequencies (2.0, 2.4 and 2.8 Hz) were established with a maximum of seven contacts required to reach a mean 'stability' based on a segmental averaging technique (Racic et al., 2009). Presumably, if the force-time curve variables exhibited intra-trial reliability then the subsequent stiffness calculations should be somewhat similar.

Given the wide use of stiffness measures, the varied methodologies and stiffness calculations employed and the limited research into the reliability of these measures, the purpose of the present study was to investigate the intra-trial and inter-day reliability and subsequent suitability of lower limb stiffness measures in adolescent female athletes and non-athletes during self-paced repeat jumping tasks. In addition, the present study sought to evaluate the impact of the data reduction method and stiffness calculation employed on the inter-day reliability of typical double-leg repeat jump tasks. It was hypothesised that measures of MSS in adolescent females would be acceptable using the most appropriate data reduction methods. Additionally it was believed that the data reduction method employed would affect the intra-trial and inter-day reliability measures.

5.3 Methods

5.3.1 Participants

Sixteen participants (six track and field athletes, seven water polo players and three ‘non-sporting’ participants) volunteered for the study (Table 5.1).

Table 5.1

Participant Descriptives (mean ± SD) for Group, Age, Height and Mass.

Participant Group	n	Age (yrs)	Height (m)	Mass (kg)
Track and Field	6	16.3 ± 1.2	1.75 ± 0.04	64.6 ± 5.0
Water Polo	7	16.0 ± 0.0	1.72 ± 0.04	69.9 ± 7.3
Non-Sporting	3	16.0 ± 1.0	1.65 ± 0.08	61.8 ± 10.9

‘Non-sporting’ participants completed <4 hours of physical activity per week outside of normal school hours (Loud et al., 2005). These activity groups were selected as part of a larger longitudinal study into lower limb MSS measures. Furthermore, it was anticipated these specific groups would display moderate MSS variability and as such provide a more rigorous evaluation of task reliability. All participants were injury free at the time of testing. Participant and parental/guardian consent for participants under 18 years of age was obtained prior to testing. The study was approved by the University Ethics Committee.

5.3.2 Test Procedure

Participants completed two identical test sessions one to two weeks apart. The participants performed a self-administered warm-up prior to each testing session. Warm-ups typically involved approximately 5 minutes of whole-body exercise (e.g. jog, pedalling on an exercise bike) followed by static and dynamic stretching. Participants completed a series of double-leg repeat jumping tasks at a self-selected jump frequency (refer to Figure 3.2 p.51). Repeat jump tasks included fifteen continuous bent-leg jumps (CJb), fifteen continuous ‘straight-leg’ jumps (CJs) and continuous bent-knee jumps for 30 seconds (CJb30). Prior to testing, participants were given a demonstration of each repeat jump task and encouraged to complete as many practice trials as required to feel comfortable that they could execute the jumps correctly. Participants jumped with hands on hips to minimize any potential influence of arm swing. Participants were instructed to jump for maximum height whilst minimizing ground contact time. Practice jumps were observed by the testers to ensure correct jump execution. Familiarization typically involved one practice trial of five to six repeat jumps. The trial was recorded once both the participant and tester were satisfied the jumps were being executed correctly. A static standing position of at least two seconds was held prior to beginning the trial to ensure the position, velocity and acceleration of the centre of mass was zero prior to the jump.

5.3.3 Data Collection and Analysis

All repeat jump tasks were performed on two force plates (Kistler, 9286A, Switzerland) sampling at 1000 Hz. These plates were previously checked across a range of expected force values (49 to 5886 N – 5 to 600 kg) and found to be accurate (r^2 = 1.00, P<0.01). Prior to testing, both plates were levelled with a three point check of vertical ground reaction forces conducted to ensure accurate force readings. The plates were covered with a Mondo track surface to provide a non-slip surface.

Jumps were performed with one foot placed on each force plate. Ground reaction forces were filtered using a dual, low-pass Butterworth filter (Bioware, Kistler, Switzerland) with a cut-off frequency of 100 Hz (Racic et al., 2009). Force-time data were then exported and analysed using a custom spreadsheet (Microsoft Office Excel 2007, Microsoft Corporation). Force data from both plates were summed to represent the forces experienced by the body's centre of mass. A force threshold of 10 N was used to indicate plate contact (Stalbom et al., 2007). Centre of mass displacement was calculated from the double integration of the vertical acceleration, obtained by dividing the vertical ground reaction force by the participant's mass (Cavagna, 1975). The double-integration method of calculating centre of mass displacement was shown to be valid for repeat jump tasks (Ranavolo et al., 2008). Peak vertical force, centre of mass displacement, contact time, flight time, jump frequency and measures of vertical leg stiffness (k_{vert}), eccentric leg stiffness (k_{ecc}), concentric leg stiffness (k_{conc}), average leg stiffness (k_{ave}) and leg stiffness using the eccentric-concentric peak force value (k_{Fi}) were calculated for each contact from each trial (Table 5.2).

Table 5.2

Musculoskeletal Stiffness Calculation Equations.

Stiffness definition	Stiffness equation	Source
Vertical stiffness (k_{vert})	$\mathbf{k_{vert}} = \frac{Fpeak}{COMecc}$ where F_{peak} = the maximum force during contact and COM_{ecc} = difference in the centre of mass displacement at contact to its lowest point (i.e. at eccentric-concentric transition)	Butler et al., 2003
Eccentric stiffness (k_{ecc})	$\mathbf{k_{ecc}} = \frac{Fecc}{COMecc}$ where F_{ecc} = the maximum force during the eccentric phase of contact (between touch-down and the eccentric-concentric transition) and COM_{ecc} = difference in the centre of mass displacement at contact to its lowest point (i.e. at eccentric-concentric transition)	
Concentric stiffness (k_{conc})	$\mathbf{k_{conc}} = \frac{Fconc}{COMconc}$ where F_{conc} = the maximum force during the concentric phase of contact (between touch-down and the eccentric-concentric transition) and COM_{conc} = difference in the centre of mass displacement between take-off and its lowest point (i.e. at eccentric-concentric transition)	based on Hunter, 2003
Average stiffness (k_{ave})	$\mathbf{k_{ave}} = \frac{\mathrm{kFi} + \mathrm{kconc}}{2}$ where k_{Fi} = eccentric-concentric stiffness and k_{conc} = concentric stiffness	
Eccentric-concentric force stiffness (k_{Fi})	$\mathbf{k_{Fi}} = \frac{Fi}{COMecc}$ where F_i = the instantaneous force at the eccentric-concentric transition during contact (i.e. at its lowest point) and COM_{ecc} = difference in the centre of mass displacement between contact and its lowest point (i.e. at eccentric-concentric transition)	based on Bosco, 1999

The most common measure of vertical stiffness during double-leg hopping tasks is k_{vert} (Butler et al., 2003), however many studies equate k_{vert} with k_{Fi} (Farley & Gonzalez, 1996). In true mass-spring behaviour it is expected that these stiffness values are equivalent, however the human system is dynamic and thus the stiffness properties of the leg spring have the potential to adjust for optimal force absorption and propulsion during a dynamic contact. Investigation into the modelling of leg MSS during gait suggests varying stiffness between impact and the absorption and propulsive phases of gait (Hunter, 2003). Thus in the present study, multiple measures of MSS were obtained including k_{ecc} and k_{conc} measures.

Due to initial data analysis and observation during testing, the first and last contacts from each trial were removed as being atypical. Four additional contacts were removed (two contacts from one trial and one contact from two other trials), based on the peak force, impulse and flight jump height calculation differences, or differences in contact time being clearly erroneous from the average jump. Additionally, some participants displayed noticeably different jump strategies between test days, as evidenced by very different jump frequencies and contact times. Participants displaying a change in jump frequency of greater than 15% and a change of contact time greater than 20% between days were excluded. This resulted in exclusions of three participants for the CJb, two participants from the CJs and three participants from the CJb30 trial.

Based on the results from Chapter 4, four methods of data reduction were used; (1) all contacts within 1SD from the average jump frequency, (2) all contacts within 5% of the average contact time, (3) the middle 5 contacts within 5% of the average contact time and, (4) all contacts within 1SD of the average contact time and with a force-displacement regression value of greater than 0.80). These were applied to each trial type to assess the impact of data reduction on inter-day reliability. For the CJb30 jump tasks, MSS values for the first ten contacts (CJb30Early) and the last ten contacts (CJb30Late) were calculated as separate values to assess any potential effects of fatigue on stiffness reliability. Following data reduction, the stiffness values of the remaining contacts were compiled for each individual for subsequent statistical analysis.

5.3.4 Statistical Analysis

The Statistical Package for Social Sciences (SPSS) version 17.0 was used for statistical analyses with an alpha level set at $p<0.05$. Normality was assessed for each data set prior to analysis using the critical appraisal approach (Peat & Barton, 2005). Heteroscedasticity was assessed using scatter plots to check the uniformity of the change in scores over the range in scores (Atkinson & Nevill, 1998). Data considered non-normal or heteroscedastistic was log-transformed prior to statistical analysis (Atkinson & Nevill, 1998).

Means ($\bar{X}$), standard deviations (SD), intra-class correlation coefficients (ICC) and coefficient of variations (CV%) were calculated for the intra-trial data sets produced by each of the data reduction criteria. In addition, inter-day bias (percentage mean difference between days), and effect sizes (ES) were calculated for the inter-day data sets. ICCs were calculated using a two-tailed mixed consistency model (Shrout & Fleiss, 1979). Data were then natural log transformed and CVs calculated using the mean square error (MSE) from a repeated measures analysis of variance (ANOVA) using the formula; CV% = $100(e^{\sqrt{\ MSE-1}})$ (Atkinson & Nevill, 1998). Percentage change between days was calculated using the log-transformed data (Hopkins, 2000). Effect size (ES) was also calculated using log-transformed data and represented the average change in the mean divided by the average of the standard deviations from both test days (Hopkins, 2000). To assist in interpretation of the overall inter-day reliability for each measure, a ratings table was developed based on previous limits for each parameter (Table 5.3). Inter-day bias categories were arbitrarily set based on reported ranges (Saunders, Pyne, Telford & Hawley, 2004) and the use of 5% as a 'typical' cut-off value in exercise science research and statistics. ICC and CV% categories were based on the cut-off value of 0.67 (McGraw & Wong, 1996) and arbitrarily set acceptance value of 10% (Atkinson & Nevill, 1996) respectively. Finally, ES categories were based on a previously established scale (Saunders et al., 2006). Values of between zero ("Poor") and three ("Excellent") were assigned based on the rating (Table 5.3). An average rating value was then calculated with a subjective 'suitability' descriptor assigned to each measure based on this value as representative of the 'overall' reliability of each measure (Table 5.3).

Table 5.3

Reliability Rating Criteria for Each Calculated Reliability Measure Including the Overall Suitability.

Descriptor	**Rating**	**Bias(%)**	**ICC**	**CV%**	**ES**	**Suitability**
Excellent (***)	3	<1.0	>0.90	<5.0	<0.2	>.2.0
Good (**)	2	1.0-2.0	0.75-0.89	5.0-10.0	0.2-0.6	1.5-2.0
Borderline (*)	1	2.1-5.0	0.67-0.74	10.1-11.0	0.7-1.2	0.75-1.45
Poor(-)	0	>5.0	<0.67	>11.0	>1.2	<0.75

5.4 Results

A summary of the intra-trial results are contained in Table 5.4. Results for the 'raw' intra-trial stiffness measures indicated poor to acceptable reliability with ICC(3,k) values of between 0.77 and 0.89 and CV(%) values between 9.8 and 16.5. Intra-trial reliability was improved using all four data reduction methods indicating generally good reliability across all measures (ICC(3,k): 0.81-0.97, CV%: 5.6-11.8%). Both data reduction methods using the contact time within 5% of the average contact time (All Contacts and Middle 5 Contacts) appeared to show generally better reliability results across the measures and repeat jump tasks.

Table 5.4

Intra-Trial Mean ± Standard Deviation (X ± SD),Intraclass Correlation (ICC) and Coefficient of Variation (CV%) for all Repeat Jump Trials, Stiffness Measures and Data Reduction Methods.

Jump and Data Reduction Method	k_{ecc}			k_{conc}			k_{vert}			k_{ave}			k_{Fi}		
	X ± SD	ICC	CV %	X ± SD	ICC	CV %	X ± SD	ICC	CV %	X ± SD	ICC	CV %	X ± SD	ICC	CV %
CJb															
- All Contacts	17.30 ± 6.06	0.82	16.3	13.10 ± 6.06	0.89	14.3	17.31 ± 6.06	0.82	16.2	14.27 ± 5.56	0.89	15.1	15.44 ± 6.22	0.88	16.5
- 3 Consec Freq 1SD	16.80 ± 5.97	0.94	9.4	12.99 ± 4.90	0.92	9.7	16.80 ± 5.97	0.94	9.4	14.16 ± 5.40	0.93	9.2	15.33 ± 5.98	0.94	9.4
- All Contacts CT 5%	17.88 ± 5.57	0.93	9.5	13.91 ± 4.60	0.97	7.0	17.88 ± 5.57	0.93	9.5	15.09 ± 5.09	0.97	6.3	16.28 ± 5.66	0.96	6.8
- Middle 5 CT 5%	17.30 ± 5.72	0.95	9.7	13.51 ± 4.97	0.96	7.2	17.30 ± 5.72	0.95	9.7	14.62 ± 5.47	0.97	6.7	15.72 ± 6.03	0.96	7.3
- All Contacts CT 1SD, r>0.80	18.25 ± 5.41	0.90	10.0	14.30 ± 4.35	0.94	9.3	18.25 ± 5.41	0.90	9.9	15.55 ± 4.73	0.95	8.8	16.80 ± 5.18	0.94	9.3
CJs															
- All Contacts	32.25 ± 9.82	0.86	11.7	24.72 ± 6.39	0.85	10.8	32.36 ± 9.81	0.86	11.7	27.89 ± 7.73	0.85	11.5	31.05 ± 9.29	0.84	12.9
- 3 Consec Freq 1SD	32.45 ± 10.36	0.94	8.1	24.63 ± 6.57	0.90	9.1	32.46 ± 10.36	0.94	8.1	27.77 ± 7.97	0.92	9.4	30.90 ± 9.68	0.91	10.8
- All Contacts CT 5%	32.40 ± 10.07	0.93	7.8	24.77 ± 6.40	0.93	7.3	32.41 ± 10.06	0.93	7.8	27.98 ± 7.79	0.94	7.4	31.19 ± 9.40	0.93	8.4
- Middle 5 CT 5%	32.67 ± 9.51	0.92	8.0	24.95 ± 6.31	0.92	7.9	32.68 ± 9.50	0.92	8.0	28.16 ± 7.57	0.93	7.9	31.37 ± 9.03	0.92	8.9
- All Contacts CT 1SD, r>0.80	32.78 ± 9.85	0.90	8.4	25.01 ± 6.30	0.92	7.9	32.79 ± 9.85	0.90	8.4	28.27 ± 7.66	0.92	8.0	31.53 ± 9.25	0.91	9.1

CJb30Early															
- All Contacts	21.82 ± 6.92	0.80	13.8	17.19 ± 4.74	0.82	11.9	21.83 ± 6.91	0.80	13.7	18.94 ± 5.57	0.80	13.0	20.69 ± 6.53	0.77	14.6
- 3 Consec Freq 1SD	21.48 ± 6.30	0.81	11.7	17.15 ± 4.29	0.90	8.0	21.48 ± 6.30	0.81	11.7	18.82 ± 5.09	0.86	9.9	20.49 ± 6.01	0.82	11.8
- All Contacts CT 5%	21.29 ± 6.49	0.91	7.9	17.12 ± 4.47	0.94	6.2	21.29 ± 6.48	0.91	7.9	18.75 ± 5.23	0.94	6.4	20.38 ± 6.09	0.92	7.5
- Middle 5 CT 5%	21.57 ± 6.31	0.95	6.9	17.21 ± 4.37	0.95	5.8	21.58 ± 6.30	0.95	7.0	18.91 ± 5.08	0.96	5.8	20.60 ± 5.91	0.96	6.5
- All Contacts CT 1SD, r>0.80	22.24 ± 6.14	0.90	8.7	17.70 ± 4.27	0.92	7.3	22.25 ± 6.13	0.90	8.7	19.44 ± 5.02	0.92	7.9	21.19 ± 5.89	0.89	9.1
CJb30Late															
- All Contacts	22.58 ± 5.96	0.83	11.1	17.40 ± 3.99	0.82	9.8	22.59 ± 5.96	0.83	11.1	19.38 ± 4.78	0.80	10.5	21.36 ± 5.83	0.78	11.7
- 3 Consec. Freq 1SD	22.21 ± 5.59	0.87	9.5	17.20 ± 3.86	0.90	6.7	22.21 ± 5.59	0.87	9.5	18.97 ± 4.79	0.87	8.4	20.74 ± 6.22	0.83	10.6
- All Contacts CT 5%	21.92 ± 5.56	0.89	7.4	16.96 ± 3.71	0.94	5.6	21.93 ± 5.55	0.89	7.4	18.79 ± 4.41	0.94	6.1	20.62 ± 5.40	0.92	7.5
- Middle 5 CT 5%	22.17 ± 5.60	0.91	6.7	17.07 ± 3.72	0.94	5.6	22.17 ± 5.60	0.91	6.7	18.85 ± 4.49	0.91	6.0	20.63 ± 5.65	0.87	7.4
- All Contacts CT 1SD, r>0.80	22.36 ± 5.79	0.90	7.5	17.37 ± 3.79	0.91	6.0	22.36 ± 5.79	0.90	7.4	19.38 ± 4.52	0.91	6.2	21.39 ± 5.37	0.90	7.4

Note. k_{ecc}: eccentric stiffness; k_{conc}: Concentric stiffness; k_{vert}: overall vertical stiffness; k_{ave}: Average of eccentric and concentric stiffness; k_{Fi}: Fi force (eccentric-concentric transition) stiffness; Freq: jump frequency; CT: contact time; Middle 5: middle five contacts; 3 Consec.: first three consecutive contacts that fit the criteria; r>0.80: force-displacement regression greater than 0.80; 1SD: one standard deviation.

Inter-day bias results (Table 5.5) ranged from a maximum of 16.7% (k_{Fi}, CJb, All Contacts CT 5%) to a minimum value of 0.3% (k_{ecc} and k_{vert}, CJs, All Contacts). The largest inter-day bias was reported for the CJb jump task with the majority of measures showing bias values of over 10%. The lowest inter-day bias scores were generally recorded for the CJs jump task with the majority of bias measures less than 2%. The ICC results generally indicated acceptable between day reliability with the majority of results above 0.67. The highest ICC values were reported for the CJb repeat trial (ICC(3,1): 0.82-0.93) with the lowest values generally reported for the CJb30Late (ICC(3,1): 0.56-0.79). The CV results generally indicated borderline reliability with the majority of results on or around the accepted 10% limit. The CV% scores ranged from 9.0% to 16.6% across the jump tasks. With the exception of the CJb30Late measures, inter-day reliability results for the 3 Consec Freq 1SD data reduction method generally showed higher CV measures across the majority of jump tasks. The ES analysis indicated trivial to small inter-day differences across all measures.

Table 5.5

Inter-Day Mean and Standard Deviation (mean ± SD), Reliability Rating and Overall Qualitative Reliability Rating (Suitability) for all Repeat Jump Tasks and Measures of Stiffness.

(a) Eccentric Stiffness (k_{ecc})

Jump and Data Reduction Method	Day 1	Day 2	Bias %	Rating	ICC	Rating	CV%	Rating	ES	Rating	Av. Rating	Suitability
CJb												
- All Contacts	17.99 ± 5.67	15.42 ± 5.26	-15.2		0.93	***	9.0	**	-0.5	**	1.75	Good
- 3 Consec Freq 1SD	16.54 ± 5.88	14.90 ± 5.31	-10.4		0.84	**	14.0		-0.3	**	1.00	Borderline
- All Contacts CT 5%	17.93 ± 5.87	15.34 ± 5.30	-15.1		0.92	***	9.1	**	-0.5	**	1.75	Good
- Middle 5 CT 5%	17.02 ± 5.57	14.79 ± 5.33	-14.2		0.92	***	10.1	*	-0.4	**	1.50	Good
- All Contacts CT 1SD, r>0.80	17.62 ± 5.68	15.42 ± 5.20	-12.9		0.92	***	9.1	**	-0.4	**	1.75	Good
CJs												
- All Contacts	34.52 ± 9.81	34.66 ± 9.83	0.3	***	0.88	**	10.8	*	0.0	***	2.25	Excellent
- 3 Consec Freq 1SD	34.69 ± 10.99	34.99 ± 10.73	0.9	***	0.76	*	14.5		0.0	***	1.75	Good
- All Contacts CT 5%	35.12 ± 10.02	34.65 ± 10.18	-1.6	**	0.88	**	11.1		-0.1	***	1.75	Good
- Middle 5 CT 5%	35.01 ± 9.83	34.60 ± 10.32	-1.7	**	0.86	**	12.2		-0.0	***	1.75	Good
- All Contacts CT 1SD, r>0.80	35.10 ± 9.97	34.54 ± 10.26	-2.0	**	0.88	**	11.3		-0.1	***	1.75	Good
CJb30Early												
- All Contacts	22.22 ± 6.30	21.29 ± 7.23	-5.4		0.92	***	9.3	**	-0.1	***	2.00	Good

- 3 Consec Freq 1SD	21.35 ± 6.05	21.11 ± 6.59	-1.5	**	0.89	**	11.3		-0.0	***	1.75	Good
- All Contacts CT 5%	21.82 ± 6.02	20.97 ± 7.31	-5.2		0.91	***	9.1	**	-0.1	***	2.00	Good
- Middle 5 CT 5%	21.37 ± 5.75	21.13 ± 7.37	-2.8	*	0.90	***	9.3	**	-0.0	***	2.00	Good
- All Contacts CT 1SD, r>0.80	21.71 ± 6.00	21.12 ± 7.43	-4.5	*	0.91	***	10.2	*	-0.1	***	2.00	Good
CJb30Late												
- All Contacts	24.88 ± 4.02	24.25 ± 6.26	-3.9	*	0.71	*	11.4		-0.1	***	1.25	Borderline
- 3 Consec Freq 1SD	24.86 ± 4.16	24.38 ± 6.45	-3.4	*	0.79	*	10.0	**	-0.1	***	1.75	Good
- All Contacts CT 5%	24.61 ± 3.68	24.16 ± 6.29	-3.4	*	0.69	*	11.5		-0.1	***	1.25	Borderline
- Middle 5 CT 5%	24.81 ± 3.76	24.14 ± 5.91	-4.0	*	0.73	*	10.3	*	-0.1	***	1.50	Good
- All Contacts CT 1SD, r>0.80	24.68 ± 3.81	24.14 ± 5.92	-3.5	*	0.73	*	10.6	*	-0.1	***	1.50	Good

Note. CJb: continuous bent-knee repeat jumps; CJs: continuous straight-leg repeat jumps; CJbEarly: average of the first 10 contacts during the CJb30s trial; CJb30 Late: average of the last 10 contacts during the CJb30 trial; Excellent: average overall reliability rating of >2; Good: average overall reliability rating of between 1.5 and 2.0; Borderline: average overall reliability rating of between 0.75 and 1.45; Poor: average overall reliability rating of <0.74; Bias%: inter-day bias as a percentage of the mean; ICC: intraclass correlation; CV%: coeffiecient of variation; ES: Cohen's effect size; Freq: jump frequency; CT: contact time; Middle 5: middle five contacts; 3 Consec.: first three consecutive contacts that fit the criteria; r>0.80: force-displacement regression greater than 0.80; 1SD: one standard deviation.

(b) Concentric Stiffness (k_{conc})

Jump and Data Reduction Method	Day 1	Day 2	Bias %	Rating	ICC	Rating	CV %	Rating	ES	Rating	Av. Rating	Suitability
CJb												
- All Contacts	17.99 ± 5.67	15.43 ± 5.26	-11.1		0.83	**	14.3		-0.3	**	1.00	Borderline
- 3 Consec Freq 1SD	16.54 ± 5.88	14.91 ± 5.31	-5.8		0.83	**	15.8		-0.2	**	1.00	Borderline
- All Contacts CT 5%	17.93 ± 5.86	15.36 ± 5.30	-11.9		0.82	**	15.2		-0.3	**	1.00	Borderline
- Middle 5 CT 5%	17.02 ± 5.57	14.80 ± 5.33	-10.2		0.83	**	16.6		-0.2	**	1.00	Borderline
- All Contacts CT 1SD, r>0.80	17.62 ± 5.68	15.44 ± 5.21	-9.2		0.82	**	13.6		-0.3	**	1.00	Borderline
CJs												
- All Contacts	34.53 ± 9.81	34.67 ± 9.83	-0.8	***	0.77	*	12.7		-0.0	***	1.75	Good
- 3 Consec Freq 1SD	34.70 ± 11.00	34.99 ± 10.73	3.0	*	0.62		16.2		0.1	***	1.00	Borderline
- All Contacts CT 5%	35.13 ± 10.02	34.65 ± 10.18	-1.8	**	0.76	*	13.5		-0.1	***	1.50	Good
- Middle 5 CT 5%	35.02 ± 9.83	34.60 ± 10.32	-1.4	**	0.69	*	15.1		-0.1	***	1.50	Good
- All Contacts CT 1SD, r>0.80	35.11 ± 9.97	34.54 ± 10.26	-2.2	*	0.77	*	13.5		-0.1	***	1.25	Borderline
CJb30Early												
- All Contacts	22.22 ± 6.30	21.30 ± 7.22	-9.1		0.73	*	12.4		-0.5	**	0.75	Borderline
- 3 Consec Freq 1SD	21.35 ± 6.05	21.13 ± 6.56	-7.9		0.59		15.8		-0.4	**	0.50	Poor
- All Contacts CT 5%	21.82 ± 6.02	20.99 ± 7.29	-10.2		0.74	*	11.7		-0.5	**	0.75	Borderline
- Middle 5 CT 5%	21.37 ± 5.75	21.16 ± 7.33	-9.2		0.76	*	11.3		-0.5	**	0.75	Borderline
- All Contacts CT 1SD, r>0.80	21.72 ± 5.99	21.13 ± 7.42	-9.7		0.71	*	12.6		-0.5	**	0.75	Borderline
CJb30Late												
- All Contacts	24.88 ± 4.02	24.25 ± 6.26	-7.7		0.56		12.8		-0.4	**	0.50	Poor
- 3 Consec Freq 1SD	24.86 ± 4.16	24.38 ± 6.45	-7.0		0.66		12.2		-0.3	**	0.50	Poor
- All Contacts CT 5%	24.61 ± 3.68	24.16 ± 6.29	-8.1		0.66		11.2		-0.5	**	0.50	Poor
- Middle 5 CT 5%	24.81 ± 3.76	24.14 ± 5.91	-7.5		0.62		11.8		-0.4	**	0.50	Poor
- All Contacts CT 1SD, r>0.80	24.69 ± 3.81	24.14 ± 5.92	-8.6		0.65		11.3		-0.5	**	0.50	Poor

(c) Vertical Stiffness (k_{vert})

Jump and Data Reduction Method	Day 1	Day 2	Bias %	Rating	ICC	Rating	CV %	Rating	ES	Rating	Av. Rating	Suitability
CJb												
- All Contacts	17.99 ± 5.67	15.43 ± 5.26	-15.1		0.93	***	9.0	**	-0.5	**	1.75	Good
- 3 Consec Freq 1SD	16.54 ± 5.88	14.91 ± 5.31	-10.2		0.84	**	13.9		-0.3	**	1.00	Borderline
- All Contacts CT 5%	17.93 ± 5.86	15.36 ± 5.30	-15.0		0.92	***	9.0	**	-0.5	**	1.75	Good
- Middle 5 CT 5%	17.02 ± 5.57	14.80 ± 5.33	-14.0		0.92	***	10.1	*	-0.4	**	1.50	Good
- All Contacts CT 1SD, r>0.80	17.62 ± 5.68	15.44 ± 5.21	-12.8		0.92	***	9.1	**	-0.4	**	1.75	Good
CJs												
- All Contacts	34.53 ± 9.81	34.67 ± 9.83	0.3	***	0.77	*	10.7		0.0	***	1.75	Good
- 3 Consec Freq 1SD	34.70 ± 11.00	34.99 ± 10.73	0.9	***	0.62		14.5		0.0	***	1.50	Good
- All Contacts CT 5%	35.13 ± 10.02	34.65 ± 10.18	-1.6	**	0.76	*	11.1		-0.1	***	1.50	Good
- Middle 5 CT 5%	35.02 ± 9.83	34.60 ± 10.32	-1.7	**	0.69	*	12.2		-0.0	***	1.50	Good
- All Contacts CT 1SD, r>0.80	35.11 ± 9.97	34.54 ± 10.26	-2.0	**	0.77	*	11.3		-0.1	***	1.50	Good
CJb30Early												
- All Contacts	22.22 ± 6.30	21.30 ± 7.22	-5.4		0.92	***	9.3	**	-0.1	***	2.00	Good
- 3 Consec Freq 1SD	21.35 ± 6.05	21.13 ± 6.56	-1.3	**	0.88	**	11.4		-0.0	***	1.75	Good
- All Contacts CT 5%	21.82 ± 6.02	20.99 ± 7.29	-5.1		0.91	***	9.1	**	-0.1	***	2.00	Good
- Middle 5 CT 5%	21.37 ± 5.75	21.16 ± 7.33	-2.5	*	0.90	**	9.2	**	-0.0	***	2.00	Good
- All Contacts CT 1SD, r>0.80	21.72 ± 5.99	21.13 ± 7.42	-4.4	*	0.91	***	10.1	*	-0.1	***	2.00	Good
CJb30Late												
- All Contacts	24.88 ± 4.02	24.25 ± 6.26	-3.9	*	0.71	*	11.4		-0.1	***	1.25	Borderline
- 3 Consec Freq 1SD	24.86 ± 4.16	24.38 ± 6.45	-3.4	*	0.79	*	10.0	**	-0.1	***	1.75	Good
- All Contacts CT 5%	24.61 ± 3.68	24.16 ± 6.29	-3.4	*	0.69	*	11.5		-0.1	***	1.25	Borderline
- Middle 5 CT 5%	24.81 ± 3.76	24.14 ± 5.91	-4.0	*	0.73	*	10.3	*	-0.1	***	1.50	Good
- All Contacts CT 1SD, r>0.80	24.69 ± 3.81	24.14 ± 5.92	-3.5	*	0.73	*	10.6	*	-0.1	***	1.50	Good

(d) Average Stiffness (k_{ave})

Jump and Data Reduction Method	Day 1	Day 2	Bias %	Rating	ICC	Rating	CV %	Rating	ES	Rating	Av. Rating	Suitability
CJb												
- All Contacts	14.80 ± 5.01	12.88 ± 4.69	-13.8		0.88	**	12.0		-0.4	**	1.00	Borderline
- 3 Consec Freq 1SD	13.95 ± 5.36	12.81 ± 4.97	-8.7		0.86	**	14.6		-0.2	**	1.00	Borderline
- All Contacts CT 5%	14.76 ± 5.05	12.77 ± 4.78	-14.5		0.88	**	12.8		-0.4	**	1.00	Borderline
- Middle 5 CT 5%	14.25 ± 5.15	12.63 ± 5.06	-12.8		0.88	**	13.9		-0.3	**	1.00	Borderline
- All Contacts CT 1SD, r>0.80	14.69 ± 4.96	13.06 ± 4.60	-11.4		0.88	**	11.2		-0.3	**	1.00	Borderline
CJs												
- All Contacts	29.34 ± 7.65	29.24 ± 7.89	-0.5	***	0.84	**	11.7		-0.0	***	2.00	Good
- 3 Consec Freq 1SD	29.12 ± 8.33	29.77 ± 8.04	2.6	*	0.69	*	15.7		0.1	***	1.25	Borderline
- All Contacts CT 5%	29.80 ± 7.82	29.27 ± 8.29	-2.2	*	0.84	**	12.4		-0.1	***	1.50	Good
- Middle 5 CT 5%	29.78 ± 7.91	29.49 ± 8.52	-1.4	**	0.79	*	13.9		-0.0	***	1.50	Good
- All Contacts CT 1SD, r>0.80	29.79 ± 7.81	29.20 ± 8.29	-2.5	*	0.84	**	12.6		-0.1	***	1.50	Good
CJb30Early												
- All Contacts	19.18 ± 4.94	17.66 ± 4.39	-7.7		0.84	**	10.9	*	-0.3	**	1.25	Borderline
- 3 Consec Freq 1SD	18.76 ± 4.90	17.59 ± 3.98	-5.3		0.70	*	14.9		-0.3	**	0.75	Borderline
- All Contacts CT 5%	19.11 ± 4.82	17.35 ± 4.27	-9.0		0.86	**	10.0	**	-0.4	**	1.50	Good
- Middle 5 CT 5%	18.83 ± 4.60	17.50 ± 4.34	-7.1		0.87	**	9.7	**	-0.3	**	1.50	Good
- All Contacts CT 1SD, r>0.80	18.98 ± 4.92	17.47 ± 4.40	-7.9		0.82	**	11.6		-0.3	**	1.00	Borderline
CJb30Late												
- All Contacts	20.84 ± 2.77	19.75 ± 4.66	-6.8		0.65		12.5		-0.3	**	0.50	Poor
- 3 Consec Freq 1SD	20.78 ± 3.10	19.90 ± 4.96	-5.9		0.75	*	11.4		-0.2	**	0.75	Borderline
- All Contacts CT 5%	20.68 ± 2.61	19.64 ± 4.56	-6.6		0.70	*	11.2		-0.3	**	0.75	Borderline
- Middle 5 CT 5%	20.59 ± 2.71	19.71 ± 4.52	-5.7		0.72	*	10.7	*	-0.2	**	1.00	Borderline
- All Contacts CT 1SD, r>0.80	20.92 ± 2.70	19.61 ± 4.45	-7.6		0.66		11.8		-0.4	**	0.50	Poor

(e) Eccentric-Concentric Stiffness (k_{Fi})

Jump and Data Reduction Method	Day 1	Day 2	Bias %	Rating	ICC	Rating	CV %	Rating	ES	Rating	Av. Rating	Suitability
CJb												
- All Contacts	16.11 ± 5.41	13.67 ± 4.94	-16.1		0.91	***	10.6	*	-0.5	**	1.50	Good
- 3 Consec Freq 1SD	15.06 ± 5.68	13.51 ± 5.26	-11.3		0.87	**	14.7		-0.3	**	1.00	Borderline
- All Contacts CT 5%	16.07 ± 5.50	13.54 ± 5.02	-16.7		0.91	***	11.3		-0.5	**	1.25	Borderline
- Middle 5 CT 5%	15.41 ± 5.47	13.31 ± 5.24	-15.1		0.91	***	12.3		-0.4	**	1.25	Borderline
- All Contacts CT 1SD, r>0.80	15.93 ± 5.34	13.85 ± 4.78	-13.3		0.91	***	9.7	**	-0.4	**	1.75	Good
CJs												
- All Contacts	32.92 ± 9.10	33.00 ± 10.03	-0.5	***	0.86	**	12.5		0.0	***	2.00	Good
- 3 Consec Freq 1SD	32.68 ± 10.12	33.40 ± 10.28	2.1	*	0.71	*	16.6		0.1	***	1.25	Borderline
- All Contacts CT 5%	33.57 ± 9.35	33.01 ± 10.51	-2.6	*	0.86	**	13.1		-0.1	***	1.50	Good
- Middle 5 CT 5%	33.42 ± 9.38	33.25 ± 10.79	-1.6	**	0.82	**	14.5		-0.0	***	1.75	Good
- All Contacts CT 1SD, r>0.80	33.56 ± 9.33	32.95 ± 10.49	-2.8	*	0.86	**	13.4		-0.1	***	1.50	Good
CJb30Early												
- All Contacts	20.90 ± 5.72	19.59 ± 5.64	-6.6		0.89	**	10.1	*	-0.2	**	1.25	Borderline
- 3 Consec Freq 1SD	20.30 ± 5.70	19.53 ± 5.17	-3.3	*	0.76	*	14.8		-0.1	***	1.25	Borderline
- All Contacts CT 5%	20.74 ± 5.57	19.13 ± 5.51	-8.2		0.91	***	9.1	**	-0.3	**	1.75	Good
- Middle 5 CT 5%	20.31 ± 5.33	19.32 ± 5.56	-5.5		0.91	***	9.3	**	-0.2	**	1.75	Good
- All Contacts CT 1SD, r>0.80	20.57 ± 5.67	19.34 ± 5.67	-6.6		0.87	**	11.5		-0.2	**	1.00	Borderline
CJb30Late												
- All Contacts	23.09 ± 3.47	22.12 ± 5.78	-6.0		0.68	*	12.7		-0.2	**	0.75	Borderline
- 3 Consec Freq 1SD	22.99 ± 3.87	22.28 ± 6.13	-5.0		0.78	*	11.3		-0.1	***	1.25	Borderline
- All Contacts CT 5%	22.80 ± 3.25	21.99 ± 5.67	-5.3		0.71	*	11.8		-0.2	**	0.75	Borderline
- Middle 5 CT 5%	22.64 ± 3.53	22.03 ± 5.50	-4.2	*	0.75	*	10.9	*	-0.1	***	1.50	Good
- All Contacts CT 1SD, r>0.80	23.20 ± 3.45	21.95 ± 5.49	-6.9		0.67	*	12.5		-0.3	**	0.75	Borderline

5.5 Discussion

Lower limb MSS measures during repeat jump tasks were generally considered reliable for adolescent females. However, the reliability of measurements varied depending upon the stiffness calculation, jump task and data reduction method employed. The inclusion of contacts within 5% of the average contact time generally appeared to improve both intra-trial and inter-day reliability across the majority of measures assessed. Similarly, by averaging stiffness measures across all available contacts, inter-day reliability improved.

The CJs and CJb30 (Early) tasks had good reliability across all measures and were acceptable test methodologies for adolescent female participants. The CJb repeat jump task appeared to have good to borderline reliability for measures of MSS. Despite indicating borderline reliability results, closer inspection of the reliability results for the CJb30Late stiffness measures suggested this task was suitable for the assessment of MSS in adolescent female athletes when the most appropriate data reduction method was applied. Results using contacts within 5% of the average contact time from the middle five contacts during the CJb30Late indicated acceptable reliability.

Good to borderline reliability results were evident for the CJb repeat jump task. The CJb task displayed a moderate inter-day bias towards lower average stiffness scores for the second day of testing. This inter-day bias was not demonstrated in the other repeat jumps, including the CJb30 trial which is essentially the same jump task over an extended period of time. The intra-trial reliability and standard deviation values from each day indicated similar variability between days. A moderate bias may reflect some form of systematic error or change in measuring equipment. Given the relatively modest and differing directions of bias results for each of the other repeat jump tasks and the previously established accuracy and linearity of the force plates (see Methods section), this is considered unlikely. It is possible that for this particular test, there was a true change in the stiffness quality of the participants. Closer inspection of the individual stiffness scores suggested the water polo group had slightly less stiffness during the second test session. For unavoidable reasons, the follow up test for water polo players was the latest of all participants, completed approximately two weeks following the initial test day. Thus, the change in the stiffness properties evident in the CJb task may be due to training or changing physical or environmental conditions. However, no obvious differences were apparent during testing and no other jump tasks, including the CJb30 repeat jump task, indicated this level of bias, so this is also considered unlikely. Although not directly reported, relatively little inter-day bias (approximately 0.5-10% for the reported mean values) is evident in previous studies of self-paced and set frequency repeat jumps (McLachlan et al., 2006; Lloyd et al., 2009). It appears the source of potential inter-day bias in MSS measures during the CJb task in the present study remains somewhat unknown. Assessment of inter-day bias during repeat jump tasks in future studies may provide further clarification.

Assessment of the suitability of the data reduction methods used in the present study suggested the use of contacts, within 5% of the average contact time was generally the most appropriate method of data reduction. Although all data reduction methods typically produced acceptable intra-trial reliability results, criteria using 5% of the average contact time generally produced better intra-trial reliability. For the majority of inter-day reliability measures, the use of all contacts within 5% of the average contact time appeared the better data reduction method of the two. The exception was the CJb30Late task for which the data reduction methods using less contacts in the average value calculated, displayed moderately better reliability results. Although the raw data indicated generally good inter-day reliability, the intra-trial reliability results failed to support the use of raw data within the current population. The apparent suitability of the raw data in the inter-day reliability results may indicate the ability of averaging stiffness values over many contacts; allowing a more accurate reflection of the underlying stiffness value for a participant. Generally, the use of more contacts in the calculation of the average stiffness scores resulted in improvements in the inter-day reliability measures. This may be indicative of inherent variability within the trial itself. Increased within trial variability in stiffness scores may also explain why the intra-trial reliability appeared more influenced by the data reduction method chosen than the inter-day reliability.

With appropriate data reduction, intra-trial reliability results showed similar levels of reliability between stiffness measures, with modestly better reliability measures for the k_{conc} measures and slightly less reliability for the k_{ecc}, k_{vert} and k_{Fi} measures. Inter-day reliability suitability would suggest the k_{ecc} and k_{vert} calculations to be slightly more reliable across the majority of measures with the k_{conc} appearing somewhat less reliable. The k_{ecc} and k_{vert} measures of MSS may in fact be more ‘sensitive’ or more appropriate measures of MSS for testing adolescents. More modest intra-trial reliability may reflect the ability of these measures to better detect contact-to-contact variation. Specifically, improved inter-day reliability may indicate an improved ability to represent the true underlying stiffness value across test days. The reverse may equally be plausible. Reduced intra-trial variability may reflect more accurate discernment of stiffness measures with greater inter-day variability reflective of increased sensitivity. By conducting follow-up test sessions within a short time period, it is assumed that the underlying MSS properties of participants should be equivocal. Although efforts were made to reduce any potential effects of fatigue, training, familiarisation or other factors such as motivation on inter-day performance, the influence of these factors remain unknown.

Although indicating acceptable intra-trial reliability the k_{conc} and k_{ave} values appeared somewhat borderline for inter-day reliability based on the suitability results. The k_{conc} measures reflected the expected 'recoil' of the leg spring. Although recoil reflected typical mass-spring type behaviour, the concentric phase may include both stored elastic energy and potential energy added by muscular contraction (Farley et al., 1991). Thus, reduced reliability during the propulsion phase of contact may reflect potential variance in energy loss and muscular contribution. It was anticipated that the k_{Fi} measure may be a more reliable measure of stiffness as it represents an 'average' stiffness during the eccentric or force absorption phase of contact. Although k_{Fi} displayed greater reliability than the k_{conc} and k_{ave} measures, measures of k_{Fi} still remained less reliable than k_{ecc} or k_{vert}.

Results from the present study indicated similar or slightly better reliability results than previous studies using similar repeat jump tasks (McLachlan et al., 2006; Lloyd et al., 2009). Similar levels of reliability were established for sub-maximal repeat jumps at 2.0 Hz and 2.5 Hz (ICC: 0.84; CV%: 9.5-13.9%) within adolescent boys (Lloyd et al., 2009). Poorer reliability results were reported for self-paced repeat jumps (ICC: 0.74; CV%: 19.1-21.4) which are more equivalent to the jumps in the present study. However, in the previous study contact mats were used to derive MSS which have been shown to have poor validity when compared to force plate measures of stiffness during self-paced maximal jumps (Lloyd et al., 2009). Additionally, previous research has indicated poor intra-trial reliability for typical stiffness measures using the first five contacts of a double-leg repeat jump task (refer to Chapter 4). Similar ICC coefficients (ICC: 0.85-0.94) within older females (age:

20.7 yrs) for leg stiffness during double-leg repeat jumps at 2.2 Hz and 3.2 Hz have previously been reported and were considered indicators of good reliability (McLachlan et al., 2006). The equivalent measure in the present study (overall stiffness measures during double-leg jumping) reported similar reliability results between the different methods of data reduction.

When assessing the results of the present study, some limitations are noted. Although both tests were conducted at similar time and day of the week, the participants' training over the test period was not controlled. Issues of fatigue and motivation may have influenced the inter-day reliability results. In addition, a two week period between tests for the water polo players was not ideal and may have allowed potential changes in stiffness measures resulting in an underestimation of the reliability between days. Given the typical nature of water polo training at this level, involving somewhat limited exposure to explosive leg related activities, it is not believed that time would have had a substantial impact on the results. The inclusion of athletic and non-athletic adolescent females in the assessment of intra-trial and inter-day reliability of MSS measures should provide some transfer of the present results to other populations. The potential variability in jump ability and motor co-ordination of these participants (Lloyd et al., 2009), may indicate the reliability results presented could trend towards the outer limits of reliability for stiffness measures. Future investigations into the impact of stiffness measures and data reduction techniques on similar repeat jumps at set frequencies within similar and dissimilar populations would add increased confidence in the selection of appropriate measures of MSS.

5.6 Conclusion

Measures of lower limb MSS during various repeat jump tasks in adolescent female athletes showed good intra-trial reliability and good to borderline inter-day reliability. In addition, the stiffness calculation used and data reduction method employed can influence the results obtained. When considering both the intra-trial and inter-day reliability results from the present study, the use of contacts within 5% of the contact time either for all contacts or the middle 5 contacts were considered the most appropriate data reduction techniques for repeat jump measures of MSS in adolescent female athletes.

CHAPTER SIX

Differences in Lower Limb Musculoskeletal Stiffness within High Level Adolescent Female Athletes from Sports with Varied Impact Loading and Non-Athletes.

This chapter forms part one of the investigation into the differences in musculoskeletal stiffness among adolescent female athletes and non-athletes. It focuses on the differences between athletes from different sporting backgrounds, including high-impact, low-impact and non-sporting participants, and potential links with performance in repeat jump tasks.

6.1 Abstract

The purpose of this study was to profile the differences in musculoskeletal stiffness and jump performance of adolescent females from high-impact and low-impact sporting populations. One hundred and thirteen adolescent females from four sub-populations, gymnastics (n = 24, high-impact), track and field (n = 30, high-impact), water polo (n = 31, low-impact) and non-sporting controls (n = 28), completed a series of continuous jump tasks on dual portable force platforms. Ground reaction forces (1000Hz) were measured during continuous bent legged repeat jumps (CJb) and continuous straight legged repeat jumps (CJs). The impact of fatigue was assessed using continuous bent legged repeat jumps for 30 seconds (CJb30). Analysis of variance (ANOVA), analysis of covariance (ANCOVA) controlling for jump frequency and body mass, and repeated measures ANCOVA with post-hoc analysis was used to identify differences in lower limb musculoskeletal

stiffness (MSS) within and between groups across the various jump measures. High-impact athletes exhibited significantly greater MSS across the repeat jump tasks when compared with controls. For low-impact athletes significant differences in MSS compared with controls were only evident during the CJs. Significant increases in jump frequency and MSS were observed with fatigue during extended continuous jumping. Greater increases in MSS were observed in high-impact athletes independent of jump frequency. It's postulated that these increases in MSS assist high-impact athletes in maintaining performance but these increases may also place these athletes at increased injury risk.

6.2 Introduction

The effective application of force is a crucial element of sports performance. Virtually all athletic activities are a result of a combination of vertical, horizontal and medio-lateral ground reaction forces (Maulder & Cronin, 2005). The measurement of force and power characteristics during closed kinetic chain, multi-joint activities that mimic the demands of sports movements may provide important information to coaches and athletes on performance. Additionally, measures of musculoskeletal stiffness (MSS), which quantify the way an athlete deals with force absorption and force application during ground contact, have been linked with greater levels of performance (Butler et al., 2003). As such, measures of MSS may be important in both performance monitoring and talent identification.

Field measures have been widely reported in the literature in the assessment of the force and power qualities of athletes. Typical measures include explosive jumps such as the counter movement jump (CMJ, e.g. Maulder & Cronin, 2005), squat jump (SJ, e.g. Smirniotou et al., 2008), drop jump (DJ, e.g. Viitasalo, Salo &

Lahtinen, 1998) and standing long jump (SLJ, e.g. Bradshaw & Le Rossignol, 2004). These field-based measures are simple and easy to administer and have been widely used by coaches, conditioners and scientists alike. Although practical, field measures typically quantify displacement during an explosive functional activity using, for example, yard sticks and contact mats and therefore fail to directly quantify the underlying force and power production properties critical to performance. Research into performance parameters in gymnasts suggests that directly quantifying force and power using force plates during typical field-based measures, may provide measures more indicative of sports performance in athletic populations than the traditional displacement measures (Bradshaw & Le Rossignol, 2004). Other recent studies highlighting the positive relationships between explosive double-leg and single-leg horizontal jumps and functional performance in team sport and sprint athletes add further evidence of the potential value of direct force assessment during field measures (Maulder et al., 2006; Holm, Stalbom, Keogh & Cronin, 2008, Moresi, Bradshaw, Greene & Naughton, 2011). During hopping type tasks, the ability to effectively resist deformation during ground contact results in the calf musculature and the Achilles tendon storing and releasing elastic energy (Kawakami et al., 2002). Thus, effective force production during functional movements includes optimal utilization of the stretch shortening cycle and elastic properties of the lower limb.

Measures of lower limb MSS model the joints, tendons, muscles and ligaments of the lower leg as a simple spring (Latash and Zatsiorsky, 1993). Such measures seek to quantify the level of resistance or compliance of the leg during ground contact, an important quality in effective energy utilization during dynamic sports activities (Butler et al., 2003). Greater lower limb resistance during contact, or MSS, has been associated with higher running velocity (Chelly & Denis, 2001), hopping frequency (Farley et al., 1991), stride frequency (Farley & Gonzalez, 1996), stride length (Derrick et al., 2000), drop landing performance (Walshe & Wilson, 1997) and running economy (Dalleau et al., 1998). Increases in MSS are generally associated with improved performance. However decreased drop jump performance, particularly under high loads, was identified for participants with high musculotendinous unit stiffness characteristics, as measured using a perturbation task (Walshe & Wilson, 1997). Thus, it would appear that while high levels of MSS are generally essential to good performance, an optimal level of compliance may be required to most effectively utilize the elastic properties of the lower limb under more extreme loading conditions (Arampatzis et al., 2001). Despite the apparent relationship between leg stiffness and performance, there appears limited research on the differences in MSS qualities between different athletic populations. An understanding of the differences in stiffness qualities between different types of athletes may assist in better evaluating effective training modalities and specific qualities required for different sporting activities. The identification of MSS differences within differing populations of high level adolescent athletes may also be useful in talent identification programs and provide normative data for comparisons in the future.

Within the limited literature exploring the differences between sporting populations and MSS and performance, greater MSS is associated with explosive, strength-trained athletes when compared to endurance athletes during counter movement jumps, drop jumps and double-leg repeat jumping (Harrison et al., 2004; Hobara et al., 2008). Additionally, although not reaching significance possibly due to small participant numbers, it would appear that greater leg stiffness may be present in high jumpers when compared to other athletes and novices during a single-leg jump task (Laffaye et al., 2005). Although limited research suggests differences between MSS during explosive jump tasks may exist within athletes from different sporting populations, it’s unclear if similar differences exist in high level adolescent athletes from more limited training experience and development.

Although measures of MSS vary within the literature, MSS is most commonly assessed during continuous double-leg repeat jumps. A modified ‘straight-leg’ repeat jump task has been used with gymnasts and appears to show potential as an indicator of ankle injury risk (Bradshaw et al., 2006). In addition, continuous double-leg repeat jumps for 30 seconds have been used to investigate potential leg power changes with fatigue in high level gymnasts (Bradshaw & Le Rossignol, 2004). A significant reduction in MSS with fatigue has been found during continuous sled jumping in recreationally active males (Kuitunen et al., 2007). However, a similar study investigating the effect of fatigue on MSS in males and females, failed to show any difference in MSS following a fatigue protocol although a trend towards increased stiffness was apparent (Padua et al., 2006). It was suggested that altered muscle activation patterns and control strategies were employed to maintain similar MSS characteristics under fatigue. Thus, it would appear the impact of fatigue on MSS remains somewhat unclear. Alterations to leg stiffness under fatigue may have important implications in regard to performance and potential injury risk. Differences in MSS and the influence of fatigue on stiffness between varied sporting populations remain unknown, particularly among high level female adolescent athletes.

The purpose of the present study was to investigate the differences in lower limb MSS between high-impact and low-impact athletic and non-athletic adolescent females. It was hypothesized that athletes from the more explosive, ’high-impact’ sports (gymnastics and track and field) would show a higher level of lower limb MSS and jump performance across all measures reflective of better elastic storage and utilization during dynamic impacts. It was further hypothesized that high-impact athletes would show minimal change in MSS under fatigue but would better maintain MSS levels and thus performance.

6.3 Methods

6.3.1 Participants

One hundred and thirteen adolescent females (28 ‘non-sporting’ participants, 30 water polo players, 24 gymnasts and 31 track and field athletes - jumpers, sprinters and middle to long distance runners) volunteered to participate in the study (Table 6.1). Additional detail on the competition level and specific events for the gymnastics and track and field groups is contained in Appendix I. ‘Non-sporting’ participants completed <4 hours of physical activity per week outside of normal school hours (Loud et al., 2005). All participants were injury free at the time of testing. Participant assent and parental/guardian consent for participants under 18 years of age was obtained prior to testing. The study was approved by the University Ethics Committee.

Table 6.1

Participant Descriptives (mean ± SD) for Group, Age, Height and Mass.

Group	**n**	**Age (yrs)**	**Height (cm)**	**Mass (kg)**
Non-Sporting	28	14.3 ± 1.1	163.9 ± 5.6	58.4 ± 9.3
Water Polo	30	16.2 ± 0.7	171.6 ± 5.8	67.3 ± 8.1
Gymnastics	24	13.7 ± 1.9	146.4 ± 8.0	39.2 ± 7.3
Track and Field	31	15.9 ± 1.2	169.0 ± 7.1	57.4 ± 6.0

6.3.2 Test Procedure

The participants performed a self-administered warm-up prior to the testing session. Warm-ups typically involved approximately 5 minutes of whole-body exercise (e.g. jog, pedalling on an exercise bike) followed by static and dynamic stretching. Participants then completed a series of jump tasks designed to assess lower limb MSS differences. To assess lower limb MSS, participants completed fifteen continuous contacts of a bent leg (CJb) and straight-leg (CJs) double-leg repeat jump task at a self-selected jump frequency. In addition the water polo, gymnasts and track and field athletes completed 30 seconds of repeat bent-leg jumps (CJb30) designed to assess the effect of fatigue on MSS measures. Thirty seconds has been used previously as a measure of anaerobic power in gymnasts (Bradshaw & Le Rossignol, 2004; Jemni et al., 2006). In addition pilot testing suggested 30 seconds provided a good balance between fatigue and task demands for high-impact and low-impact sporting groups. Non-sporting controls did not complete the fatigue task due to concerns over potential injury risk due to the increased demands of the CJb30. A self-selected jump frequency was chosen to enable lower limb MSS assessment where participants are able to self-regulate their chosen MSS and jump frequency (Padua et al., 2005).

Prior to the task completion, participants were given a demonstration of each jump task and encouraged to complete as many practice trials as required to feel comfortable that they could execute the jumps correctly. Participants jumped with hands on hips to minimize any potential influence of arm swing. During the repeat jump tasks participants were instructed to jump continuously as high as possible whilst minimising ground contact (Dalleau et al., 2004). This was done to maintain the performance aspect of the task whilst attempting to ensure the consistency of the contacts and limiting any potential influence of differences in ground contact time on the MSS measures (Arampatzis et al., 2001; Hobara et al., 2008). Practice jumps were observed by the testers to ensure correct jump execution. Familiarization typically involved one practice trial of five to six repeat jumps. The trial was recorded once both the participant and tester were satisfied the jump was being executed correctly. A static standing position of at least two seconds was held prior to beginning of each trial to ensure accuracy of the initial conditions. Full recovery was allowed between trials with a minimum of approximately 1 to 2 minutes between different jump types.

6.3.3 Data Collection and Analysis

All repeat jump tasks were performed on two force plates (Kistler, 9286A, Switzerland) sampling at 1000 Hz. These plates have been previously checked across a range of expected force values (49 to 5886 N – 5 to 600 kg) and found to be accurate ($r^2 = 1.00$, $P<0.01$). Prior to testing, both plates were levelled and a three point check of vertical ground reaction forces conducted to ensure accurate force readings. The plates were covered with a Mondo track surface to provide a non-slip surface.

Ground reaction forces were filtered using a dual, low-pass Butterworth filter (Bioware, Kistler, Switzerland) with a cut-off frequency of 100 Hz (Racic et al., 2009). Force-time data were then exported and analysed using a custom spreadsheet (Microsoft Office Excel 2007, Microsoft Corporation). A force threshold of 10 N was used to indicate plate contact (Stalbom et al., 2007).

Measures of lower limb MSS were including vertical stiffness (k_{vert}), average eccentric stiffness (k_{Fi}), concentric stiffness (k_{conc}) and eccentric stiffness (k_{ecc}) values were obtained for all jumps based on measures used in previous literature. Calculation details are obtained in Table 5.2, p92. Centre of mass displacement was calculated from the double integration of the vertical acceleration, obtained by dividing the vertical ground reaction force by the participant's mass (Cavagna, 1975). The double-integration method of calculating centre of mass displacement was shown to be valid for repeat jump tasks (Ranavolo et al., 2008). Measures of MSS during repeat jumps have been shown to be reliable in adolescent female populations (refer to Chapter 5).

Peak vertical force, centre of mass displacement, contact time, flight time, jump frequency and measures of vertical leg stiffness (k_{vert}), eccentric leg stiffness (k_{ecc}), concentric leg stiffness (k_{conc}), average leg stiffness (k_{ave}) and leg stiffness using the eccentric-concentric peak force value (k_{Fi}) were calculated for each contact. Based on intra and inter-trial reliability assessment, only contacts within 5% of the average contact time across the trial were included. For the CJb30 jump task, the first contact was excluded (as per the other repeat trials). The next ten contacts (contacts 2 to 11) were analysed and represented MSS during the initial part of the trial (CJb30Early). With the exception of the final contact which was excluded as per the other repeat jumps, the final ten contacts were analysed separately and represented MSS under fatigue (CJb30Late). The final value for each parameter represented an average of the values for each contact that was within 5% of the average contact time for that trial.

6.3.4 Statistical Analysis

The Statistical Package for Social Sciences (SPSS) version 17.0 was used for statistical analyses with an alpha level set at $p<0.05$. Normality was assessed for each data set prior to analysis using the critical appraisal approach (Peat & Barton, 2005). Data considered non-normal was log-transformed prior to statistical analysis (Atkinson & Nevill, 1998).

Analysis of variance (ANOVA) and analysis of covariance (ANCOVA) using jump frequency and body mass as covariates with Bonferroni post-hoc analysis were conducted for stiffness measures from the repeat jump tasks. MSS has previously been shown to be directly related to jump frequency (Farley et al., 1991) and body mass (Padua et al., 2005).

Because the impact of fatigue on MSS was the focus for the CJb30s jump task a repeated measures analysis of variance (ANOVA) and repeated measures analysis of covariance (ANCOVA) controlling for jump frequency and body mass were conducted to look at changes in MSS and any potential difference between groups.

6.4 Results

6.4 1 Repeat Jump Tasks

Comparison of jump frequencies between groups is contained in Figure 6.1. MSS results for the repeat jump tasks (CJb, CJs and CJb30) are contained in Table 6.2. Both 'raw' and co-varied MSS values are reported. Results for k_{vert} and k_{ecc} were identical across all tests so only k_{vert} is reported in the summary results.

Across all tests the highest MSS values were recorded for k_{vert} measures. The lowest MSS values were recorded for k_{conc} measures with k_{ave} and k_{Fi} returning slightly higher but remarkably similar MSS values. Although some variation in stiffness values was evident, group comparisons and post-hoc analysis revealed nearly identical differences between groups irrespective of MSS measure used. Additionally, correlations of stiffness values across MSS measures indicated extremely high and significant relationships between variables (Table 6.3).

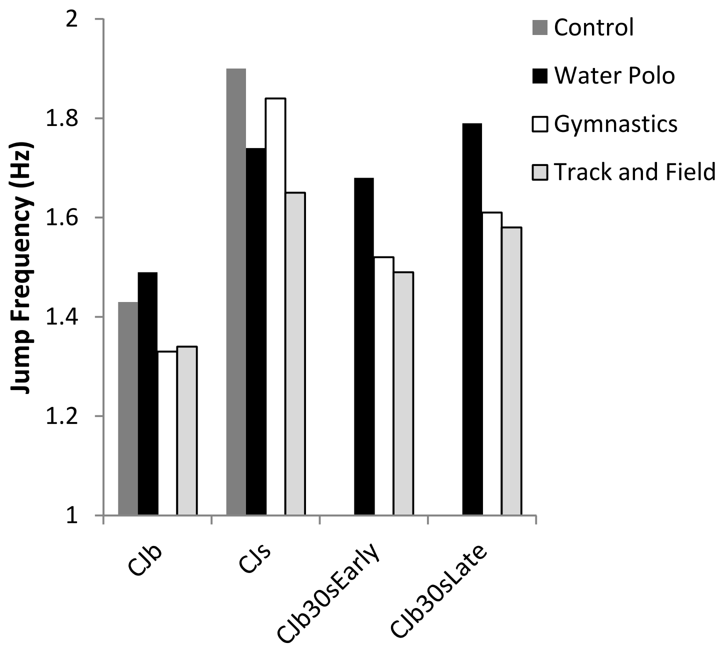

Figure 6.1 Jump frequency comparison between groups for all repeat jump tasks.

Note. CJb: bent knee continuous repeat jumps; CJs: straight-leg continuous repeat jumps; CJb30sEarly: average data from the first 10 contacts during the bent knee continuous jumps for 30 seconds; CJB30sLate: average data from last 10 contacts during the bent knee continuous jumps for 30 seconds.

During the CJb jump tasks a significant difference between groups was found with post-hoc analysis indicating water polo players had significantly higher MSS than both the controls and gymnasts. MSS was also significantly lower for the gymnasts compared with the track and field athletes during the CJb task. Analysis of covariance adjusting for jump frequency and body mass also suggested significant differences between groups; however post-hoc analysis revealed this was only between the track and field and control groups. Gymnasts displayed comparable levels of stiffness with track and field athletes but post-hoc analysis did not reveal any significant differences from any other groups.

Of the repeat jumps, the highest MSS (13.3-31.8 kN/m) measures were recorded during the CJs task. Statistical analysis revealed a significant difference between groups with post-hoc analysis indicating the controls were significantly different from the water polo and track and field athletes. Water polo and track and field athletes displayed the highest level of leg stiffness during this task, with the gymnasts slightly lower and the controls displaying the lowest level of MSS. Although adjusted results suggested similar differences between water polo athletes and non-sporting controls, post-hoc analysis also revealed a significant difference between controls and gymnasts. Track and field athletes and gymnasts had the highest co-varied MSS scores with water polo next and controls recording the lowest level of co-varied leg stiffness.

Table 6.2

Group Comparisons for 'Raw' (mean ± standard deviation) and Co-Varied (cv; estimated mean ± standard error) Musculoskeletal Stiffness Measures During the Repeat Jump Tasks.

Jump Task	JH (%Height)	k_{vert} (kN/m)	k_{Fi} (kN/m)	k_{conc} (kN/m)	k_{ave} (kN/m)	k_{vert} -cv (kN/m)	k_{Fi}-cv (kN/m)	k_{conc}-cv (kN/m)	k_{ave}-cv (kN/m)
CJb									
Control	0.08^{gtw} ± 0.02	11.69^{w} ± 5.84	9.05^{w} ± 5.79	8.69^{w} ± 4.60	8.87^{w} ± 5.16	10.69^{t} ± 0.83	8.04^{gt} ± 0.68	7.89^{gt} ± 0.56	7.96^{gt} ± 0.61
Water Polo	0.10^{cgt} ± 0.02	16.44^{cg} ± 5.01	14.22^{cg} ± 4.91	12.40^{cg} ± 3.68	13.31^{cg} ± 4.27	12.09 ± 0.93	10.14 ± 0.76	9.10 ± 0.64	9.62 ± 0.69
Gymnastics	0.13^{cw} ± 0.02	8.22^{tw} ± 4.37	6.64^{tw} ± 4.39	6.46^{tw} ± 3.46	6.55^{tw} ± 3.91	14.00 ± 1.23	11.80^{c} ± 1.01	10.71^{c} ± 0.84	11.25^{c} ± 0.91
Track & Field	0.12^{cw} ± 0.02	13.43^{g} ± 8.00	11.16^{g} ± 7.26	10.23^{g} ± 6.02	10.70^{g} ± 6.60	14.44^{c} ± 0.79	12.40^{c} ± 0.65	11.16^{c} ± 0.54	11.78^{c} ± 0.59
CJs									
Control	0.06^{gtw} ± 0.02	18.15^{t} ± 5.27	16.93^{tw} ± 5.06	15.76^{tw} ± 4.38	16.35^{tw} ± 4.67	14.97^{gtw} ± 1.07	13.67^{gtw} ± 0.99	13.30^{gtw} ± 0.74	13.48^{gtw} ± 0.84
Water Polo	0.08^{cgt} ± 0.02	22.70 ± 5.68	21.92^{c} ± 5.66	19.37^{c} ± 3.79	20.65^{c} ± 4.63	20.26^{ct} ± 1.12	19.82^{ct} ± 1.03	17.66^{ct} ± 0.77	18.74^{ct} ± 0.88
Gymnastics	0.11^{cw} ± 0.03	20.35 ± 7.85	19.93 ± 7.88	17.43 ± 5.37	18.68 ± 6.56	24.16^{c} ± 1.49	23.18^{c} ± 1.38	20.10^{c} ± 1.03	21.64^{c} ± 1.17
Track & Field	0.11^{cw} ± 0.03	23.04^{c} ± 8.32	21.90^{c} ± 7.56	19.26^{c} ± 6.11	20.58^{c} ± 6.74	25.52^{cw} ± 1.02	24.53^{cw} ± 0.95	21.22^{cw} ± 0.70	22.87^{cw} ± 0.80

Note. JH: Jump height as a percentage of standing height; k_{vert}: overall vertical stiffness; k_{Fi}: eccentric-concentric stiffness; k_{conc}: concentric stiffness; k_{ave}: average stiffness; k_{ecc}: eccentric stiffness; $k_{vert\text{-}cv}$: overall vertical stiffness covaried for jump frequency and body mass; $k_{Fi\text{-}cv}$: eccentric-concentric stiffness covaried for jump frequency and body mass; $k_{conc\text{-}cv}$: concentric stiffness covaried for jump frequency and body mass; $k_{ave\text{-}cv}$: average stiffness covaried for jump frequency and body mass; $k_{ecc\text{-}cv}$: eccentric stiffness covaried for jump frequency and body mass. ANOVA Bonferroni post-hoc analysis: c: indicates significant ($p<0.05$) difference from the control group; g: indicates significant ($p<0.05$) difference from the gymnast group; t: indicates significant ($p<0.05$) difference from the track and field group; w: indicates significant ($p<0.05$) difference from the water polo group; CJb: continuous bent-knee repeat jumps; CJs: continuous streaight-leg repeat jumps.

Table 6.3

Correlations Between Stiffness Calculations for Each Repeat Jump Task with Vertical Stiffness (k_{vert}) Measures.

Jump Task	**k_{Fi} (kN/m)**	**k_{conc} (kN/m)**	**k_{ave} (kN/m)**	**k_{ecc} (kN/m)**
CJb	0.96**	0.93**	0.95**	1.00**
CJs	0.98**	0.90**	0.96**	1.00**
CJb30Early	0.98**	0.94**	0.97**	1.00**
CJb30Late	0.99**	0.94**	0.97**	1.00**

Note. CJb: continuous bent-knee repeat jumps; CJs: continuous straight-leg repeat jumps; CJb30Early: average of the first 10 contacts from continuous bent-knee jumps performed for 30 seconds; CJb30Late: average of the last 10 contacts from continuous bent-knee jumps performed for 30 seconds; k_{Fi}: eccentric-concentric stiffness; k_{conc}: concentric stiffness; k_{ave}: average stiffness; k_{ecc}: eccentric stiffness; * denotes significance $p<0.05$ (two-tailed), ** denotes significance $p<0.01$(two-tailed).

6.4.2 Fatigue Jump Task

Jump frequency increased significantly from the beginning to the end of the CJb30 trial, $F(1,87) = 150.05$, $p<0.001$ (Figure 6.2). There were also significant differences between groups for jump frequency ($F(2,87) = 11.68$, $p<0.001$) but no interaction effect ($F(2,87) = 0.61$, $p>0.05$).

As with the CJb and CJs results, results of the CJb30 test revealed remarkably similar results across all MSS measures. k_{Fi} measures are presented due to their wide use in the literature and their approximate ‘middle’ stiffness scores across jump tasks. As with jump frequency, measures of MSS increased between the beginning and end of the CJb30 trial (Figure 6.3). A significant difference between the start and end of the CJb30 trial ($F(1,87) = 42.18$, $p<0.001$) with an increase in MSS across all groups was found. Similarly, a significant difference between groups was identified ($F(2,87) = 14.83$, $p<0.001$). Post-hoc analysis identified significant difference

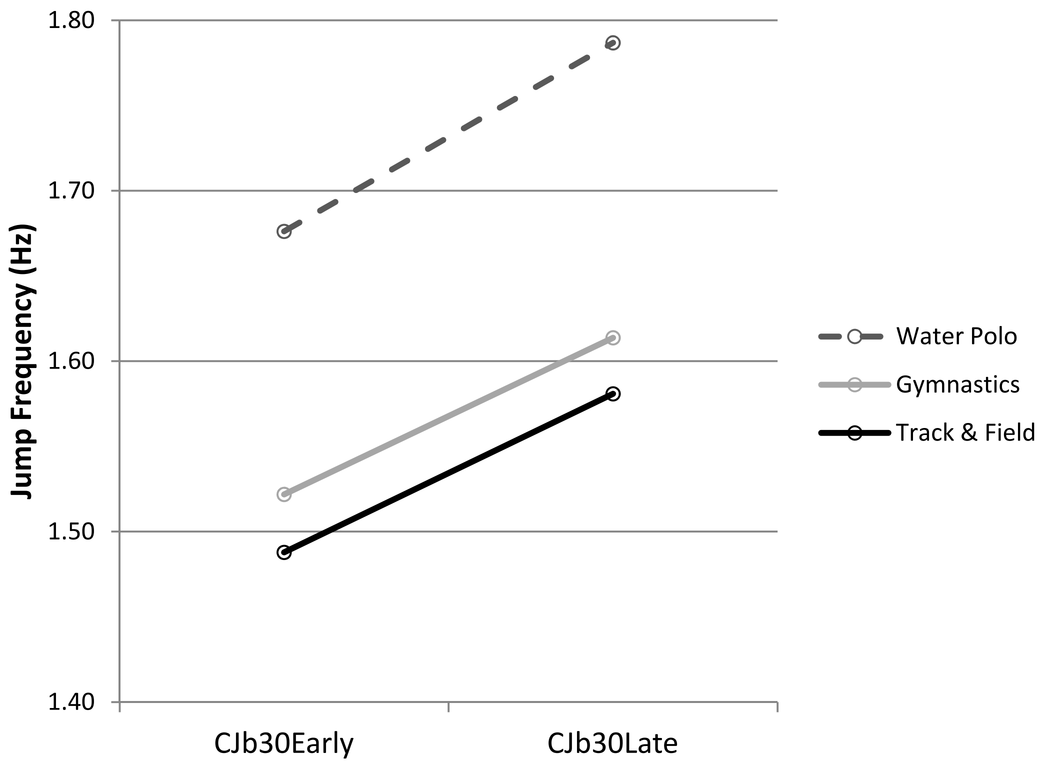

Figure 6.2 Jump frequency comparison between groups and within groups during the 30 second continuous bent-knee repeat jumps comparing jump frequency from the first ten contacts (CJb30Early) to the last ten contacts (CJb30Late).

between all groups with water polo athletes having the highest level of MSS and gymnasts the least amount of leg MSS. No interaction effect between group and time was found, $F(2,87) = 2.35$, $p>0.05$. Whilst no interaction effect was revealed, it would appear that both water polo and gymnasts experience similar increases in MSS from the beginning to the end of the CJB30s trial with track and field athletes displaying slightly greater increases in MSS.

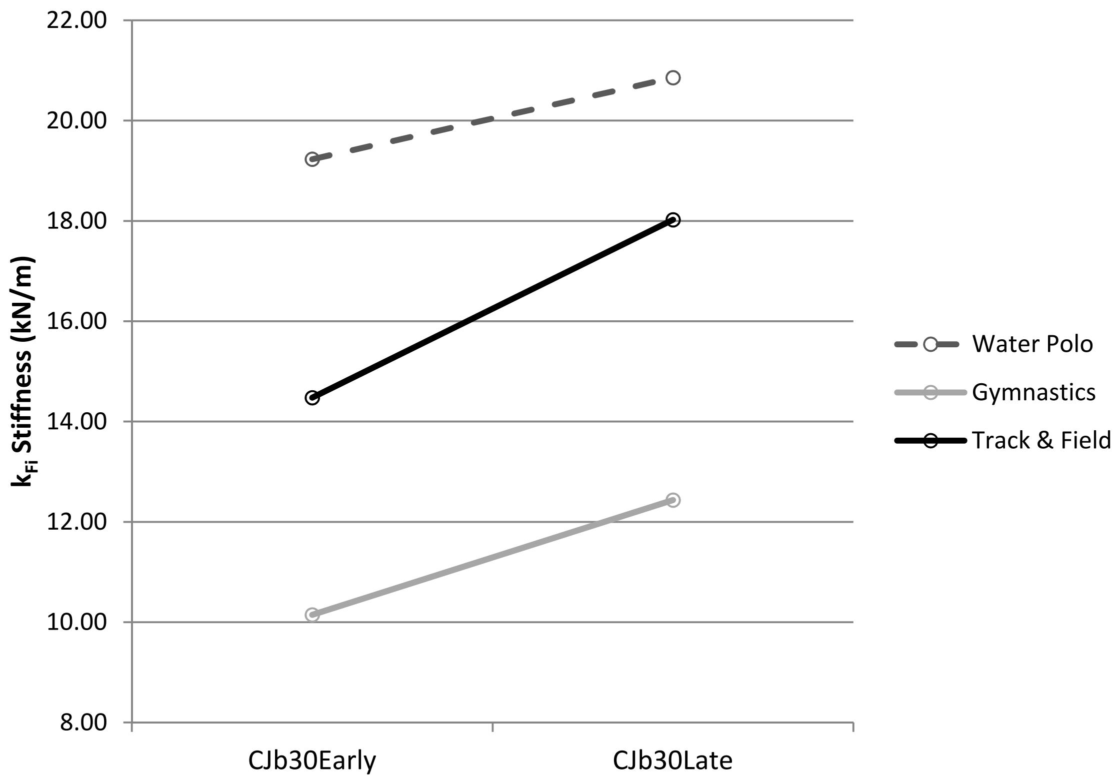

Figure 6.3 Musculoskeletal eccentric-concentric stiffness (k_{Fi}) comparison between groups and within groups during the 30 second continuous bent-knee repeat jumps comparing jump frequency from the first ten contacts (CJb30Early) to the last ten contacts (CJb30Late).

Results for MSS changes during the CJB30s jump task when controlling for jump frequency and body mass identified a significant difference between leg MSS for the first 10 contacts compared with the final 10 contacts, $F(1,84) = 57.743$, $p<0.001$. Although approaching significance, no significant differences were found between groups, $F(2,84) = 2.85$, $p>0.05$. No interaction effect was obtained (Figure 6.4).

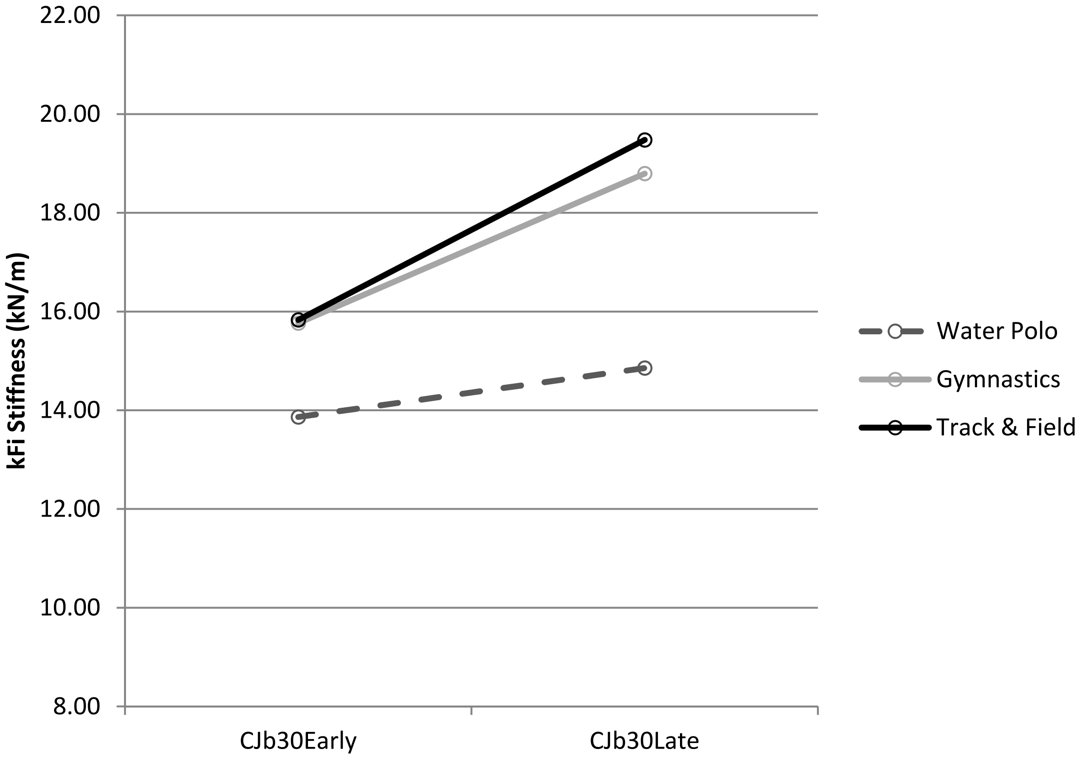

Figure 6.4 Estimated musculoskeletal eccentric-concentric stiffness (k_{Fi}) mean value comparison between groups and within groups controlling for jump frequency and body mass during the 30 second continuous bent-knee repeat jumps comparing jump frequency from the first ten contacts (CJb30Early) to the last ten contacts (CJb30Late).

6.5 Discussion

6.5.1 Repeat Jump Tasks

Once MSS values were controlled for jump frequency and body mass, the hypothesis that high-impact athletes (gymnasts and track and field athletes) would generally display greater levels of lower limb MSS and jump performance was supported by the present study.

Consideration of the ‘raw’ MSS values during the CJb suggests very different results to the co-varied MSS results within the same trial. Gymnasts recorded the lowest ‘raw’ leg MSS measures during the CJb task (6.64 kN/m) with water polo athletes displaying the highest values (14.22 kN/m). Track and field athletes and controls had MSS levels somewhere in between these two extremes. It was anticipated that gymnasts and track and field athletes would display greater levels of MSS and jump performance during a dynamic repeat jump tasks such as the CJb. Closer inspection of the data suggests the high ‘raw’ stiffness values recorded for the water polo players may have been influenced by their greater jump frequency in comparison with the high-impact groups. Both the controls and water polo athletes’ MSS values may therefore have been ‘artificially’ inflated due to their relatively higher jump frequency. Additionally, with a body mass of nearly half that of the water polo athletes, the gymnasts’ MSS results may reflect lower absolute peak forces. Body mass has been shown to be related to MSS measures during locomotion in animal studies (Farley et al., 1991) and in studies comparing males and females during similar repeat jump tasks (Padua et al., 2005). When MSS was co-varied for jump frequency and body mass differences, the high-impact athletes displayed similar stiffness values that were significantly higher than non-sporting controls. This higher level of leg MSS was associated with significantly greater jump heights between groups.

Previous literature has associated greater MSS with strength and power athletes when compared with endurance athletes (Harrison et al., 2004; Hobara et al., 2008). The benefit of greater MSS to successful performance in explosive, power-type sports such as gymnastics and track and field appears supported among adolescent female athletes. The optimization of leg stiffness aids in maximizing mechanical power during dynamic ground contacts (Arampatzis et al., 2001). It’s suggested that the observed greater levels of MSS reflect enhanced ability to utilize the elastic components of the musculoskeletal system to more effectively store and return energy (Butler et al., 2003). The ability of gymnasts and track and field athletes to exhibit higher levels of MSS reflects an important quality crucial to high-level performance in these sports.

During the CJs, 'raw' measures of MSS were far more similar across the three sporting groups than in the CJb task. Despite lower body mass, the gymnasts had a higher jump frequency during the CJs task which may explain why their MSS measures are more similar to the other sporting groups than for the CJb. Controls displayed lower levels of 'raw' leg MSS when compared to the sporting populations. When controlling for frequency and body mass, similar results to the CJb task are evident although MSS scores appear somewhat more 'polarized'. This may reflect greater ankle joint stiffness differences within the high-impact athletes than the combination of ankle and knee joint stiffness influencing the CJb task. Adjustment of stiffness at the ankle joint may be a more dominant mechanism among high-impact athletes. However, the more 'polarizing' effect of the CJs task may simply reflect the greater demands of this task which makes it a more sensitive measurement tool for MSS differences. The contribution of joint stiffness to the leg MSS adjustment remains somewhat unclear throughout the literature. Conflicting findings support greater emphasis on ankle joint stiffness changes (Farley & Morgenroth, 1999) and knee joint stiffness changes (Hobara et al., 2009) as the primary mechanism of leg stiffness adjustment in double-leg repeat jumps. Joint stiffness adjustment at both the knee and ankle joints are proposed as the mechanisms for adjusting MSS during jumping (Farley & Morgenroth, 1999; Hobara et al., 2009) with knee stiffness regulation thought to be more critical at higher running velocities (Arampatzis et al., 1999; Kuitunen et al., 2002). Further research into joint stiffness contributions within MSS differences in adolescent female athletic populations may provide further insight into the influence of joint mechanics and sport-specific training on MSS adjustment.

6.5.2 Musculoskeletal Stiffness and Fatigue

During the CJB30s fatigue task, both the high-impact and low-impact sporting groups showed increased levels of jump frequency with corresponding increases in MSS during the latter stages of the trial. Previous research would suggest that muscle activation and recruitment strategy is altered to maintain vertical stiffness following fatigue (Padua et al., 2006). However, the same study indicated a moderate trend towards increases in vertical stiffness with fatigue although this was not significant. Further research into fatigue indicates a decrease in MSS with fatigue for sub-maximal repeat jumps on a sled apparatus in recreationally active males (Kuitunen et al., 2007).

When changes in MSS under fatigue were compared, following controlling for differences in jump frequency and body mass, gymnasts and track and field athletes showed remarkably similar MSS adjustments. Both groups increased their leg MSS with fatigue. Whilst water polo players also increased MSS under fatigue, gymnasts and track and field athletes displayed even greater increases under fatigue than water polo athletes. This is evident despite similar increases in jump frequency across the groups. Although the exact mechanisms and strategy of these changes remains unclear, an increase in MSS may assist in more effectively storing and utilizing elastic energy during the latter stages of the jump task when the muscles are experiencing fatigue. This may be a mechanism used by high-impact athletes to aid in maintaining performance levels. Unfortunately, this same mechanism of increasing

MSS to maintain performance when fatigued may also place high-load athletes at increased injury risk.

The mean self-selected frequencies in the present study ranged from approximately 1.3 Hz to 1.9 Hz. These values are lower than previously reported self-selected jump frequencies (around 2.2 Hz) in similar tasks (Padua et al., 2005). Self-selected jump frequency was generally lower during the CJb task and higher for the CJs task. Additionally, self-selected jump frequencies were dissimilar between groups. Gymnasts and track and field athletes tended to select lower jump frequencies for the CJb jump tasks. The track and field and water polo groups had lower self-selected jump frequencies for the CJs task. Previous research suggests double-leg repeat jumps performed at jump frequencies below approximately 2.2 Hz fail to exhibit mass-spring behavior (Farley et al., 1991). This was not the case in the present study with force-displacement regressions across all jump tasks reflecting a high relationship between force and displacement during the eccentric phase of contact (Figure 6.5). The lower self-selected jump frequencies reported in the present study may reflect the instructions given to participants. Participants were asked to jump as high as possible whilst minimizing ground contact time. This may have lead to higher jump heights and corresponding greater flight times which resulted in lower comparative jump frequencies. Given the participants in the present study were adolescents not adults as in previous studies, differences in self-selected jump frequency may reflect the potential influence of maturation. However, further research is required before any possible links between growth and self-selected jump frequency can be established.

Measures of ‘raw’ MSS recorded for participants from the present study appear somewhat lower (9.1 – 21.9 kN/m) than similar self-paced double-leg jumps for females in previous literature; mean values of 19 kN/m and 21.6 kN/m (Granata et al., 2002b; Padua et al., 2005). However, the age and body mass of the participants in the present study is also lower than previous literature which may account for the difference in MSS scores. In addition, differences in methodology and stiffness calculation methods make MSS comparison somewhat difficult. In the only other study to assess MSS in young athletes, similar levels of MSS were found for repeat jumps at 2.0 Hz and for five maximal repeat jumps (Lloyd et al., 2009) which displayed a similar jump frequency of approximately 1.6-1.9 Hz. Preliminary adjustments of the mean values reported for MSS measures and body mass from previous research involving female participants would suggest lower MSS exhibited across all groups for the CJb task with comparable levels

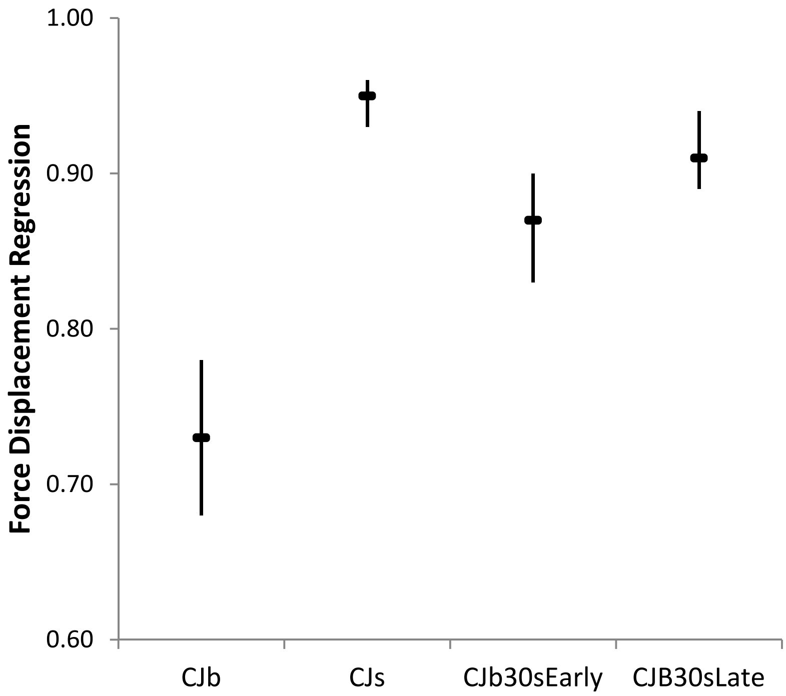

Figure 6.5 Group force-displacement regression coefficients (mean ± 95% confidence intervals) for each repeat jump task.

Note. CJb: continuous bent-leg repeat jumps; CJs: continuous straight-leg repeat jumps; CJb30sEarly: initial 10 contact average during the 30 second continuous bent-leg repeat jump task; CJb: last 10 contact average during the 30 second continuous bent-leg repeat jump task.

of MSS for the CJs. Future investigation into potential differences between athletes of different maturity and training age and MSS where stiffness scores can be adjusted for jump frequency and body mass differences may provide some interesting insights into the development of MSS characteristics across the maturing athlete.

Although the different calculations of MSS returned different values, it would appear that the measures differ proportionally within participants. For example, a participant with a high vertical stiffness relative to the other participants will have a high value for the other measures of MSS. Thus, for between subject comparisons, any value of MSS is appropriate. However, when comparing participant values across different studies the MSS calculation used should be considered as variations in MSS value may be present. As previously mentioned, in true mass-spring behavior, k_{vert} and k_{Fi} should be equal however it would appear that based on the present results these values are moderately different.

6.6 Conclusion

Athletes from high-impact sports (gymnastics and track and field) show greater levels of lower limb MSS when compared to low-impact sports (water polo players) and non-sporting adolescent females. It is postulated that this reflects more effective utilization of elastic energy storage and return during dynamic contacts. Although not statistically significant, participation in some sporting activity, including low-impact sports such as water polo, also appears associated with moderately higher lower limb MSS. Thus, it appears that greater MSS is associated with successful performance in explosive, power sports within adolescent female athletes. Although athletes increase jump frequency and subsequent MSS under fatigue, high-impact athletes display larger increases in MSS independent of increases in jump frequency compared with low-impact athletes. In addition to differences in sporting demands, increased MSS under fatigue may place high-impact athletes at increased injury risk.

CHAPTER SEVEN

Longitudinal Musculoskeletal Stiffness Changes in Adolescent Females from High-impact Sporting, Low-Impact Sporting and Non-Sporting Populations.

This chapter investigates the longitudinal changes in musculoskeletal stiffness within adolescent female athletes and non-athletes across a 12 month period. By longitudinally investigating changes in musculoskeletal stiffness the interaction between lower limb stiffness, growth and sport-specific training can be explored.

7.1 Abstract

The purpose of the present paper was to investigate the impact of growth and sports-specific training on musculoskeletal stiffness across a 12 month period in high-impact and low-impact sporting and non-sporting adolescent females. Eighty-three adolescent females from four sub-populations representing high-impact sport (gymnastics and track and field), low-impact sport (water polo) and a non-sporting group volunteered for the study. Ground reaction forces were measured during a series of jump tasks using dual force plates at baseline and 12 months later. Continuous bent legged repeat jumps (CJb), continuous straight legged repeat jumps (CJs) and continuous bent legged jumps for thirty seconds (CJB30) were performed at a self-selected frequency during both test occasions. Measures of lower limb musculoskeletal stiffness were obtained for each jump and compared between participant groups and across time using repeated measures analysis of variance

(ANCOVA). Longitudinal results generally displayed similar differences between groups to baseline MSS differences. The high-impact athletes exhibited greater levels of stiffness than low-impact athletes and controls. Comparisons of MSS changes within sports suggest a complex interaction between growth, sport-specific training, performance and MSS adaptation.

7.2 Introduction

Measures of musculoskeletal stiffness (MSS) have been linked with both performance and injury (Butler et al., 2003). However, few studies have directly investigated the links between training, performance and MSS. Particularly for the developing athlete, there is a paucity of literature assessing the influence of sport-specific training and growth on longitudinal changes to lower limb MSS.

Little research has been conducted investigating the differences between different populations of athletes and measures of MSS. Increased levels of MSS in strength and power athletes compared with endurance athletes may suggest potential sport-specific adaptations (Harrison et al., 2004; Hobara et al., 2008). Comparison of a single-leg jump for height between different explosive sporting populations (volleyball, basketball, handball and high jumpers) with a novice group, found no significant difference between stiffness measures (Laffaye et al., 2005). Although statistical significance was not reached, the results displayed greater levels of stiffness in high jumpers when compared with the other groups. Despite apparent differences in body mass, none of these studies co-varied for body mass which has been shown to influence MSS (Farley et al., 1991). In addition, these studies were all cross-sectional in nature, and as such, are limited in regards to potential observations of sport-specific training on MSS.

Few studies have looked at the impact of training on longitudinal changes to MSS. Whilst previous literature has shown changes to tendon stiffness properties and jump performance with short-term training (Kubo, Yata, Kanehisa & Fukunaga, 2006; Burgess et al., 2007; Kubo et al., 2007), those measures investigated particular adaptations to elastic structures in the lower extremity, and utilised different methodologies than measures of MSS. One such investigation included additional measures of ankle joint stiffness and identified improved jump performance in healthy untrained males following twelve weeks of plyometric training (Kubo et al., 2007). A weight-trained group within the same study displayed small but non-significant increases in jump performance and ankle joint stiffness. An additional study investigating the impact of a 6-week plyometric training program on running economy in male runners suggested increases in ankle stiffness, as measured using a perturbation protocol, improved running economy leading to improved performance (Spurrs, Murphy & Watsford, 2003). Although previous literature supports the link between sport-term 'explosive' training and MSS changes, longer-term stiffness adaptations due to growth and sports participation remain unknown. Particularly within the high level adolescent athlete, the impact of sports-specific participation and maturation on MSS and subsequent performance and increased injury risk is unclear.

The purpose of the present study was to longitudinally investigate the impact of high level sports participation on lower limb MSS in adolescent female athletes. It was hypothesized that high level adolescent female athletes involved in high-impact sports participation would display increases in MSS across a 12 month period. It was believed that changes in MSS would be minimal in athletes involved in low-impact sports (water polo players) and non-sporting controls.

7.3 Methods

7.3.1 Participants

Eighty-three adolescent females from four sub-populations representing high-impact sports (gymnastics and track and field), low-impact sports (water polo) and non-sporting controls completed both the baseline and 12-month test session and were considered for the present study (Table 7.1). At the time of the 12-month test session, five gymnasts and two track and field athletes had an existing injury and were unable to complete the follow up jump tasks. In addition, the CJb trial for one non-sporting participant did not capture properly on the force plates and was omitted from subsequent analysis for that jump task.

Table 7.1

Participant Age, Height and Body Mass at Baseline and 12-Months, Reported as Mean ± Standard Deviation.

Group	**n**	**Baseline**			**12 months**	
		Age (yrs)	Height (m)	Mass (kg)	Height (m)	Mass (kg)
Controls	26	14.4^{tw} ± 1.0	163.9^{gtw} ± 5.8	58.9^{gw} ± 9.4	164.9^{gtw} ± 5.9	59.9^{gw} ± 10.6
Water Polo	18	15.9^{cg} ± 0.7	170.7^{cg} ± 5.1	66.2^{cgt} ± 8.1	171.5^{cg} ± 5.4	68.1^{cgt} ± 7.7
Gymnastics	17	13.5^{tw} ± 1.5	145.6^{ctw} ± 8.2	38.1^{ctw} ± 6.7	150.8^{ctw} ± 7.9	43.0^{ctw} ± 6.9
Track & Field	22	15.5^{cg} ± 1.1	169.1^{cg} ± 7.0	58.0^{gw} ± 5.2	170.2^{cg} ± 6.8	59.6^{gw} ± 5.5

Note. ANOVA Bonferroni post-hoc analysis: c: indicates significant ($p<0.05$) difference from the control group; g: indicates significant ($p<0.05$) difference from the gymnast group; t: indicates significant ($p<0.05$) difference from the track and field group; w: indicates significant ($p<0.05$) difference from the water polo group.

7.3.2 Test Procedure

Warm-up, familiarisation and jumps testing were conducted as per the test procedure at baseline, outlined in detail in Chapter 5.

For the sporting populations, both test sessions corresponded with what was considered a major competition so that a full training year was evaluated. In track and field this corresponded to the National under age championships, for gymnastics it was the National clubs championships and in water polo the National under age championships.

7.3.3 Data Collection and Analysis

Data collection, processing and analysis were completed as per baseline testing outlined in Chapter 5. Based on baseline results indicating similarities between k_{Fi}, k_{conc} and k_{ave} stiffness measures, combined with high correlations between different measures of lower limb MSS, only the k_{vert} and k_{Fi} stiffness measures are reported in the present chapter.

7.3.4 Statistical Analysis

The Statistical Package for Social Sciences (SPSS) version 17.0 was used for all statistical analyses with an alpha level set at $p<0.05$. Normality was assessed for each data set prior to analysis using the critical appraisal approach (Peat & Barton, 2005). Data considered non-normal was log-transformed prior to statistical analysis (Atkinson & Nevill, 1998).

Repeated measures analysis of covariance (ANCOVA) controlling for jump frequency and body mass with Bonferroni post-hoc analysis was used to identify significant differences in MSS for the participant group and time main effects as well as any interaction between these two variables. Jump frequency and body mass were used as covariates as they have previously been shown to be related to differences in MSS (Farley et al., 1991; Padua et al., 2005). Repeated measures ANCOVA assumptions were assessed for the data prior to statistical analysis. Paired samples t-tests were conducted to compare baseline and 12-month MSS changes within each participant group for each jump task. In addition, the percentage difference was calculated for within group measures using the following equation;

$$\%\text{Difference } (\%\text{Diff}) = ((\text{measure}_{\text{baseline}} - \text{measure}_{\text{12months}}) / (\text{measure}_{\text{baseline}}) \times 100.$$

Comparison of changes to MSS under fatigue during the CJb30 jump task was assessed using a repeated measures analysis of covariance (ANCOVA) for each participant group. Changes to MSS across the CJb30 trial were compared (early contacts compared with late contacts) for any potential differences from baseline and 12-month tests. Significance for all tests was set at $p<0.05$.

7.4 Results

Descriptive comparisons of jump performance changes and MSS components are contained in Table 7.2. Summary MSS results for longitudinal analysis during the continuous repeat jump measures are contained in Table 7.3. Overall ANCOVA main and interaction effect results for each jump task are contained in Table 7.4.

7.4.1 Repeat Jump Tasks

For the CJb task, a significant main effect between baseline and 12 months was found for k_{Fi} but not for k_{vert} (Table 7.4). Main effects between groups were also obtained for both stiffness measures during the CJb jump task. Post-hoc analyses for differences between groups are identified in Table 7.3. Statistical analysis revealed a significant interaction effects between group and time of test for k_{vert} but not for k_{Fi}.

Table 7.2

Descriptive Comparison (mean ± standard deviation) between Baseline (0m) and 12 Months (12m) for all Repeat Jump Tasks.

Jump Task	**JH (%Height)**			**F_{peak} (BW)**			**COMd (m)**		
	0m	12m	%Diff	0m	12m	%Diff	0m	12m	%Diff
CJb									
- Control	0.08 ± 0.02	0.08^{gt} ± 0.02	5.1	3.89 ± 0.69	3.88^{t} ± 0.51	-0.1	0.20 ± 0.04	0.19 ± 0.03	-4.2
- Water Polo	0.10 ± 0.02	0.09^{gt} ± 0.02	-8.5*	4.37 ± 0.56	4.04 ± 0.64	-7.6	0.19 ± 0.02	0.19 ± 0.04	2.0
- Gymnastics	0.13 ± 0.03	0.13^{cw} ± 0.02	-5.0	4.66 ± 1.52	4.32 ± 1.04	-7.4	0.22 ± 0.07	0.21 ± 0.03	-2.9
- Track & Field	0.12 ± 0.03	0.14^{cw} ± 0.03	12.2^	4.35 ± 1.13	4.99^{c} ± 1.15	14.8*	0.21 ± 0.07	0.20 ± 0.06	-13.2*
CJs									
- Control	0.06 ± 0.02	0.06^{gt} ± 0.02	0.3	4.25 ± 0.50	4.27^{gt} ± 0.67	0.4	0.14 ± 0.03	0.13 ± 0.02	-5.8
- Water Polo	0.08 ± 0.02	0.06^{gt} ± 0.02	-23.3^	4.82 ± 0.56	4.48^{gt} ± 0.48	-7.0*	0.15 ± 0.02	0.13 ± 0.03	-10.6^
- Gymnastics	0.12 ± 0.03	0.08^{cw} ± 0.03	-26.7^	6.17 ± 0.93	5.54^{cw} ± 0.93	-10.1	0.13 ± 0.03	0.12 ± 0.03	-7.5
- Track & Field	0.11 ± 0.03	0.10^{cw} ± 0.03	-6.9	5.38 ± 0.99	5.60^{cw} ± 1.16	4.2	0.15 ± 0.03	0.13 ± 0.03	-12.9^
CJb30 Early									
- Water Polo	0.08 ± 0.02	0.08^{gt} ± 0.02	-3.5	4.60 ± 0.50	4.21 ± 0.69	-8.5	0.16 ± 0.02	0.17 ± 0.04	12.2
- Gymnastics	0.12 ± 0.03	0.12^{w} ± 0.03	-1.2	5.29 ± 0.96	5.47 ± 1.09	-6.8	0.17 ± 0.04	0.18 ± 0.04	6.8
- Track & Field	0.11 ± 0.03	0.12^{w} ± 0.03	9.7*	4.74 ± 1.10	5.16 ± 1.06	8.8	0.19 ± 0.05	0.17 ± 0.05	-6.7
CJb30 Late									
- Water Polo	0.06 ± 0.01	0.06^{gt} ± 0.02	-1.2	4.40 ± 0.44	4.12^{gt} ± 0.60	-6.3	0.14 ± 0.02	0.16 ± 0.04	13.2
- Gymnastics	0.11 ± 0.03	0.10^{w} ± 0.03	-7.8	5.43 ± 1.12	5.47^{w} ± 1.09	0.6	0.15 ± 0.05	0.15 ± 0.05	-0.4
- Track & Field	0.10 ± 0.03	0.11^{w} ± 0.03	5.6	5.03 ± 0.97	5.10^{w} ± 0.93	1.3	0.16 ± 0.06	0.17 ± 0.05	2.2

Note. CJb: continuous bent-knee repeat jump task; CJs: continuous straight-leg repeat jump task; CJb30Early: first 10 contacts during the 30 seconds continuous bent-knee repeat jump task; CJb30Late: last 10 contacts during the 30 seconds continuous bent-knee repeat jump task; %Diff: the percentage difference from baseline measures; JH: jump height expressed as a percentage of standing height; F_{peak}: peak vertical ground reaction force expressed as times body mass; COMd: centre of mass displacement during the eccentric phase of ground contact; c: post-hoc analysis indicates a significant group difference from the controls; g: post-hoc analysis indicates a significant group difference from the gymnasts; t: post-hoc analysis indicates a significant group difference from the track and field athletes; w: post-hoc analysis indicates a significant group difference from the water polo players; * repeated measures t-test $p<0.05$; ^ repeated measures t-test $p<0.01$.

Table 7.3

Jump Frequency (Freq) and Musculsoskeletal Stiffness Measures Comparison (mean ± standard deviation) between Baseline (0m) and 12 Month (12m) Test Sessions.

Jump Task	Freq (Hz)			k_{vert} –cv (kN/m)			k_{Fi} –cv (kN/m)		
	0m	12m	%Diff	0mth	12mth	%Diff	0mth	12mth	%Diff
CJb									
- Control	1.45 ± 0.24	1.56^{gt} ± 0.18	7.1	10.64 ± 4.47	10.79^{gt} ± 2.01	1.4	7.17 ± 1.68	8.68^{gt} ± 1.28	21.0
- Water Polo	1.49 ± 0.12	1.55^{gt} ± 0.17	3.9	11.39 ± 3.33	11.95^{t} ± 2.28	4.9	9.08 ± 1.29	10.53^{t} ± 1.22	15.9*
- Gymnastics	1.33 ± 0.21	1.38^{cw} ± 0.18	3.1	15.22 ± 4.40	13.50^{c} ± 3.66	-11.3	12.13 ± 1.33	11.98^{c} ± 1.25	-1.2
- Track & Field	1.32 ± 0.21	1.42^{cw} ± 0.17	7.6	13.62 ± 4.13	17.41^{cw} ± 4.73	27.8^	11.39 ± 1.34	15.65^{cw} ± 1.32	37.4^
CJs									
- Control	1.90 ± 0.20	1.93 ± 0.15	2.0	14.38 ± 1.33	17.77^{gt} ± 1.30	23.5^	13.61 ± 3.50	17.93^{gt} ± 4.60	31.7^
- Water Polo	1.76 ± 0.12	1.94 ± 0.24	10.5^	18.78 ± 1.23	19.49^{gt} ± 1.21	3.8	18.64 ± 4.08	19.28^{gt} ± 3.27	3.4
- Gymnastics	1.81 ± 0.19	1.98 ± 0.26	9.3*	24.18 ± 1.23	25.72^{cw} ± 1.23	6.3	23.81 ± 5.01	25.65^{cw} ± 5.16	7.7
- Track & Field	1.63 ± 0.15	1.74 ± 0.26	7.2*	23.07 ± 1.30	27.54^{cw} ± 1.34	19.3^	23.00 ± 5.69	28.24^{cw} ± 8.49	22.8^
CJb30 Early									
- Water Polo	1.68 ± 0.10	1.64^{gt} ± 0.16	-2.5	14.06 ± 3.96	12.76^{gt} ± 3.31	-9.3	12.81 ± 3.67	11.15^{gt} ± 2.20	-13.0
- Gymnastics	1.51 ± 0.27	1.53^{w} ± 0.16	1.1	19.65 ± 5.14	16.91^{w} ± 4.25	-14.0*	17.76 ± 4.20	15.49^{w} ± 3.28	-12.8*
- Track & Field	1.49 ± 0.17	1.50^{w} ± 0.21	1.1	16.85 ± 4.61	19.43^{w} ± 5.39	15.3*	15.38 ± 4.53	18.23^{w} ± 5.56	18.6*
CJb30 Late									
- Water Polo	1.80 ± 0.10	1.75^{t} ± 0.18	-3.0	14.79 ± 3.97	13.81^{gt} ± 3.57	-6.6	13.59 ± 3.39	12.49^{gt} ± 3.14	-8.1
- Gymnastics	1.61 ± 0.32	1.69 ± 0.24	5.0	22.19 ± 4.69	20.82^{w} ± 5.20	-6.2*	20.76 ± 4.10	19.36^{w} ± 4.41	-6.8*
- Track & Field	1.59 ± 0.19	1.57^{w} ± 0.22	-0.9	20.37 ± 5.88	20.76^{w} ± 4.83	1.9	19.05 ± 6.20	19.48^{w} ± 5.17	2.2

Note. k_{vert} –cv: vertical stiffness adjusted for jump frequency and body mass; k_{Fi} –cv: eccentric-concentric stiffness adjusted for jump frequency and body mass; CJb: continuous bent-knee repeat jump task; CJs: continuous straight-leg repeat jump task; CJb30Early: first 10 contacts during the 30 seconds continuous bent-knee repeat jump task; CJb30Late: last 10 contacts during the 30 seconds continuous bent-knee repeat jump task; Hz: jumps per second; kN/m: KiloNewtons per metre; c: post-hoc analysis indicates a significant group difference from the controls; g: post-hoc analysis indicates a significant group difference from the gymnasts; t: post-hoc analysis indicates a significant group difference from the track and field athletes; w: post-hoc analysis indicates a significant group difference from the water polo players; * repeated measures t-test p<0.05; ^ repeated measures t-test p<0.01, Similar results were identified for the CJs jump task with significant main effects for both differences between baseline and 12 months and between groups. Significant interaction effects were found for k_{Fi} measures of MSS during the CJs jump task. The interaction between test session and participant group for measures of k_{vert} approached significance but was not statistically significant.

Table 7.4

Analysis of Covariance (ANCOVA) Results for the Overall Main and Interaction Effects Comparing Group and Test Session Measures of Musculoskeletal Stiffness (MSS) during Each Jump Task.

MSS Measures	**Main Effects**				**Interaction Effect**	
	Time		Group			
	F (1, 71)	p	*F* (3, 71)	p	*F* (3, 71)	p
CJb						
- k_{vert}	1.790	0.185	11.270	0.000	4.724	0.005
- k_{Fi}	12.769	0.001	17.778	0.000	1.980	0.125
CJs						
- k_{vert}	17.903	0.000	20.830	0.000	2.425	0.073
- k_{Fi}	26.636	0.000	21.854	0.000	3.575	0.018
CJb30Early						
- k_{vert}	0.557	0.459	8.730	0.001	6.209	0.004
- k_{Fi}	0.323	0.572	10.684	0.000	7.142	0.002
CJbLate						
- k_{vert}	0.761	0.387	16.077	0.000	0.536	0.589
- k_{Fi}	0.937	0.338	16.270	0.000	0.680	0.511

Note. CJb: continuous bent-knee repeat jump task; CJs: continuous 'straight-leg' repeat jump task; CJb30Early: average of the first 10 contacts during 30 seconds of continuous bent-knee repeat jumps; CJbLate: average of the last 10 contacts during 30 seconds of continuous bent-knee repeat jumps; *F*: F-value result; p: probability value; k_{vert}: measures of overall vertical leg stiffness; k_{Fi}: measures of musculoskeletal stiffness using the eccentric-concentric transition force.

7.4.2 Fatigue Jump Task

No significant main effect was identified between sessions (baseline and 12 months) for either the CJb30sEarly or CJb30sLate stiffness measures. However, significant differences between groups were found for musculoskeletal measures during both the CJb30Early and CJb30sLate measures. Significant interaction effects were identified during the CJb30sEarly task however no interaction effects were identified for CJ30sLate MSS measures. Although repeated measures ANCOVA did not show an overall difference between test sessions, repeated measures t-tests indicated a significant reduction in stiffness for gymnasts. Track and field athletes showed a significant increase in MSS during the early contacts of the fatigue task. Although water polo athletes appeared to show a decrease in both early and late measures of MSS, subsequent t-tests failed to show a significance difference between baseline and 12 months for either of these measures.

Repeated measures ANCOVA main and interaction effect results within each participant group for the CJb30 jump task are contained in Table 7.5. Statistical analysis comparing the effect of fatigue across the baseline and 12 month test session within each group indicated a significant difference between MSS measures early in the trial to stiffness measures late in the trial following fatigue. No significant main effect stiffness differences were found between test sessions (baseline and 12 month). However, repeat measures t-tests indicated a significant difference between both early and late MSS measures for the gymnasts. The track and field athletes also displayed a significant difference in stiffness at 12 months for the early contacts during the CJb30s. An interaction effect between the early and late contacts across the baseline and 12 month tests was reported for the track and field athletes. Representative curves are presented in Figure 7.1.

Table 7.5

Analysis of Covariance (ANCOVA) Results for Overall Main and Interaction Effects Comparing Fatigue and Test Session Measures of Musculoskeletal Stiffness (MSS) within each Participant Group.

MSS Measures	**Main Effects**				**Interaction Effect**	
	Fatigue		Test Session		F-value	p
	F-value	p	F-value	p		
Water Polo*						
- k_{vert}	5.020	0.032	0.945	0.338	0.168	0.684
- k_{Fi}	9.924	0.003	1.922	0.175	0.704	0.407
Gymnastics^						
- k_{vert}	41.843	0.000	0.578	0.454	1.038	0.317
- k_{Fi}	63.388	0.000	0.790	0.382	0.281	0.600
Track & Field#						
- k_{vert}	24.748	0.000	0.060	0.808	5.130	0.029
- k_{Fi}	30.881	0.000	0.312	0.580	7.009	0.012

Note. * degrees of freedom were *df*(1,34); ^ degrees of freedom were *df*(1,27); # degrees of freedom were *df*(1,40); p: probability value; k_{vert}: measures of overall vertical leg stiffness; k_{Fi}: measures of musculoskeletal stiffness using the eccentric-concentric transition force.

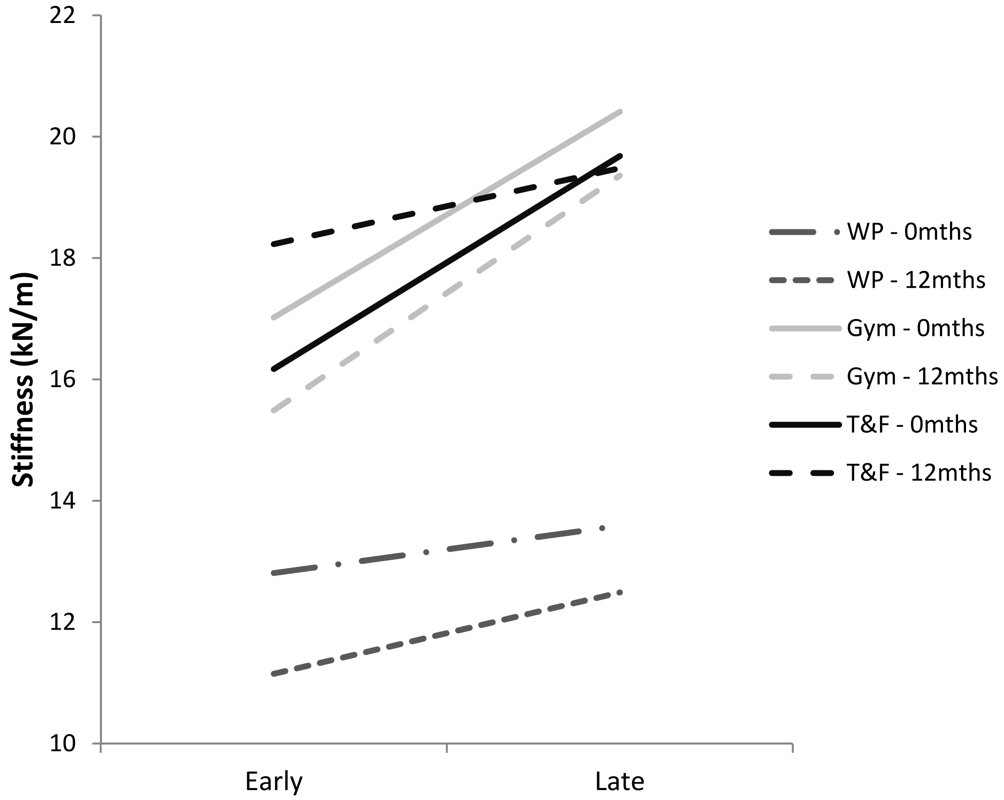

Figure 7.1 Comparison of fatigue on eccentric-concentric stiffness (k_{Fi}) measures during the CJb30s test comparing CJb30sEarly ("Early") and CJb30sLate ("Late") by test session within each participant group; water polo (WP), gymnastics (Gym) and track and field (T&F).

7.5 Discussion

7.5.1 Repeat Jump Tasks

The results of the present study generally suggest that there is an influence of sport-specific training and growth on increases in MSS. However the relationship between growth, training and longitudinal stiffness changes remains somewhat complex.

Track and field athletes displayed increases in lower limb stiffness across both the CJb and CJs tasks. Particularly for, although not limited to, the CJb jump task these changes are greater than the percentage changes that occur for all other groups. Given similar changes in height and mass compared with the water polo players and controls, it is suggested that these increases in MSS may reflect the impact of training. Interestingly, it's evident from the percentage changes that the increase in lower limb stiffness was greater in the CJb than the CJs within the track and field athletes. Previous research would suggest that increases in running velocity, particularly during sprinting type activities, are predominantly influenced by increases in knee joint stiffness (Arampatzis et al., 1999; Kuitunen et al., 2002). Thus, it would appear that the specific training for track and field events had a positive influence on the CJb jump tasks which involves modulating stiffness at both the knee and ankle joints. The CJs task is designed to predominantly assess ankle joint stiffness differences. The present results would suggest that training for track and field also influenced increases in ankle stiffness. Although stiffness modulation during running may be predominantly modulated at the knee joint, increases in stiffness at both the ankle and knee joint are associated with increases in running velocity (Arampatzis et al., 1999). As such, the results support the suggestion that athletics training influences increases in both ankle and knee joint stiffness in high level adolescent female athletes.

It was hypothesized that athletes from both high-impact groups would show longitudinal increases in stiffness across all jump measures. Whilst the track and field athletes appeared to show increases in stiffness across both jump tasks, the potential impact of training on MSS in gymnasts appears somewhat less clear. The gymnasts showed no significant changes in MSS for either jump task. Although the gymnasts displayed a trend towards increases in stiffness during the CJs task, k_{vert} indicated a trend towards a decrease in stiffness during the CJb. These results may suggest moderate to little influence of gymnastics training on MSS, despite gymnasts still maintaining high levels of leg stiffness relative to track and field, water polo and non-sporting participants. The lower leg stiffness longitudinal trend in the gymnast group would suggest that any potential training effects mainly influences ankle joint stiffness. The majority of gymnastics training and competition is generally performed on sprung surfaces with movements that are often characterized by repeat contacts and jumps with low ground contact times. Performance in floor and vault ability has been linked to increased CJs jump power but decreased CJb jump power (Bradshaw & Le Rossignol, 2004). Thus, the CJs task may be a more indicative of the impact of gymnastics training on leg stiffness, albeit somewhat limited from the present results.

The apparent lack of longitudinal stiffness change in response to training appears somewhat contradictory given gymnasts display high relative MSS compared with other athletic populations. The answer may lie in the potential impact of growth and maturation. Comparisons of the longitudinal height and mass data suggest that the gymnasts were in a period of rapid growth during the 12 month test period when compared with the other participant groups. Mean increases of approximately 5 cm in height and 5 kg in body mass were experienced in the gymnastics group over the 12 month period. Comparison of 'raw' MSS change in the gymnasts appears to indicate 'moderate' longitudinal stiffness gains in CJs stiffness (Figure 7.2), however these gains are not sufficient to influence their 'relative' stiffness measures (when covaried for body mass). In effect the rapid growth experienced by the gymnasts during this period may be somewhat 'out pacing' any potential training gains experienced resulting in little to no relative stiffness change. With lower limb stiffness changes linked to both performance and potential injury risk (Butler et al., 2003), these relative changes may warrant consideration from coaches and conditioners when considering training loads, recovery and performance outcomes. Future assessment of MSS in the coming years may indicate similar improvements in stiffness to the track and field athletes as the gymnasts' growth spurt slows down.

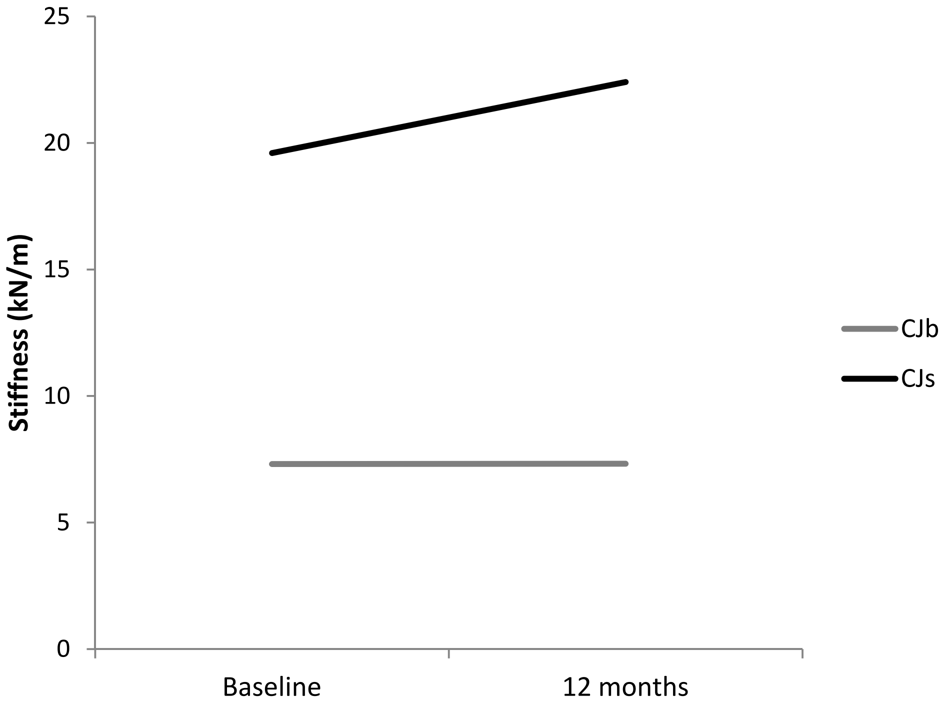

Figure 7.2 Longitudinal changes (baseline to 12 months) in 'raw' eccentric-concentric stiffness (k_{FI}) measures for both continuous bent-knee (CJb) and continuous straight-leg (CJs) repeat jump tasks in gymnasts.

Note. CJb: continuous bent-knee repeat jumps; CJs: continuous straight-leg repeat jumps.

It was anticipated that the water polo players and non-athletes would show relatively little to no increases in MSS during the 12 month period. Both water polo players and controls displayed an increase in k_{Fi} stiffness during the CJb task, although this was not significant within the controls. Controls also displayed increased stiffness for the CJs task. Although controls displayed improvements in MSS, they still displayed lower limb stiffness levels below the sporting groups. Although not specifically involved in organized sport, non-sporting participants may have had a positive influence on MSS from maturation, activities of daily living and participation in compulsory physical education classes. It might be expected that the sporting groups would also display these general improvements in stiffness in addition to training adaptations. However, the sporting participants already displayed greater MSS, presumably due to previous training and exposure to attenuating higher impact loads. This may ‘negate’ any potential general affects of growth and daily living on MSS. Interestingly, the water polo athletes appeared to show a moderate increase in k_{Fi} stiffness during the CJb task. Although it was not anticipated that training and competition during a weight-supported sporting activity such as water polo with limited lower limb impacts would improve lower limb stiffness, it is possible that sports participation or a related training activity that may have been undertaken, such as resistance training, may have led to the changes in what appears to be predominantly knee joint stiffness.

7.5.2 Musculoskeletal Stiffness and Fatigue

Comparison of MSS changes during the CJb30 task indicated similar longitudinal results in the gymnasts and water polo players. Although their relative MSS values were relatively lower at the 12 month test session, similar stiffness changes under fatigue were observed. It would appear that stiffness adjustment under fatigue is relatively consistent among the water polo and gymnast groups irrespective of longitudinal stiffness changes.

The track and field athletes still indicated an increase in stiffness with fatigue however this adjustment was much more minimal during the 12 month testing compared with baseline. Interestingly the final level of stiffness was extremely similar for both test sessions under fatigue irrespective of the relative starting points earlier in the trial. Previous research into fatigue and stiffness changes indicate a shift to a more ankle dominant stiffness strategy under fatigue that may be reliant on muscular activation of the calf muscles to avoid fatigue (Padua et al., 2006; Kuitunen et al., 2007). The increase in early stiffness exhibited by the track and field athletes may represent potential training-induced improvements in knee joint stiffness control serving to improving jump performance and efficiency in the early stages of the trial. In the latter stages of the CJb30 task however, as the lower limb muscles begins to fatigue, similar values of MSS are present as this represents optimal use of the elastic structures of the lower leg including the Achilles tendon. Future research into the potential longitudinal effects of various sports participation on stiffness modulation under fatigue, with an emphasis on regulatory mechanisms, may provide more insight into the nature of these relationships.

In spite of some varied longitudinal stiffness changes within athlete and non-athlete populations, gymnasts and track and field athletes maintain significantly increased MSS across all measures when compared to non-sporting populations. These findings appear consistent with the concept that increased levels of leg stiffness are an important component in high-impact sports such as gymnastics and track and field. Although water polo players did not exhibit significantly greater stiffness levels than controls, it would appear that even within body supported sports, such as water polo, there is a trend toward increased levels of stiffness in comparison to non-sporting participants. Although not immediately intuitive this apparent increase in stiffness may be sport related or potentially related to some form of activity or training within the sport. The impact of genetics on MSS was out of the scope of the present study, however it must be considered as a potential influence on MSS differences between groups.

Self-selected jump frequency generally displayed slight increases from baseline to 12 month testing. Increases of approximately 2 to 10% were recorded longitudinally. Although there was a general increase across all groups these frequencies of 1.4 Hz (CJb) and 1.8 Hz (CJb) at baseline (mean age = 14.9 ± 1.4 years) and 1.5 Hz (CJb) and 1.9 Hz (CJs) 12-months later were still lower than preferred jump frequencies of approximately 2.2 Hz for adults that has been reported in previous literature (Granata et al., 2002b). Increases in jump frequency may reflect a number of potential differences including growth, potential training adaptations, motivation or increases in stiffness. However, the general trend across all groups may suggest some kind of interaction between maturation and self-selected jump frequency. This may be worthy of further investigation.

Although the focus of the present study was to look at longitudinal changes in stiffness within adolescent females from specific sporting populations, any differences in training or competition schedules were not controlled for. As high level junior sportswomen, it would not have been viable to control participant's training schedules at such a critical time in their respective careers. As such, the results of the present study may potentially be influenced by any differences in training techniques, volume, loading or the specific training phase the athletes were in. Changes in strength and body composition have been related to training and training phases in gymnasts (Sands, Irvin & Major, 1995). Testing within the participation groups were conducted around the major national competition for the sports and at the same time of year which should have reduced the impact of potential training differences however it should be acknowledged that any variance may have influenced the present findings.

7.6 Conclusion

Although it would appear lower limb MSS longitudinal changes are evident among adolescent female athletes and non-athletes, it remains somewhat unclear as to the influence of the sport nature on these changes. Whilst increased stiffness is evident within high-impact sport populations compared to low-impact sport athletes and non-sporting participants, both relative increases (track and field athletes) and no changes (gymnasts) to stiffness measures were observed within the high-impact athletes. It is suggested changes to MSS in gymnasts may have been influenced by the rapid period of growth experienced by this group during the test period. Further research is needed to explore the unique adjustments and mechanisms underlying these adjustments within specific sporting populations, particularly for the developing athlete at such a critical time in their sporting career. An understanding of longitudinal musculoskeletal stiffness adjustment in athletic populations may aid in both performance enhancement and injury prevention within high level adolescent athletes.

CHAPTER EIGHT

The Development of a Kinetic Model to Prospectively Predict Increased Injury Risk in High Level Adolescent Females from High-Impact Sports

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This chapter explores the potential of musculoskeletal stiffness measures from high-impact female adolescent athletes to prospectively predict lower limb injury risk. The ability to accurately identify potential 'at risk' athletes from field based testing may provide important information to coaches and athletes. Moreover, successful prediction models may lead to early intervention strategies for potential injury prevention.

8.1 Abstract

The purpose of the present chapter was to investigate the ability of kinetic jump measures (e.g. musculoskeletal stiffness), to predict lower limb injury risk in adolescent females participating in high-impact sports. Eighty-three adolescent females from gymnastics, track and field, water polo and a non-sporting group completed two test sessions at baseline and 12 months later. A series of jump tasks were performed on two force plates to assess measures of lower limb musculoskeletal stiffness. In addition, site specific markers of bone health were measured for the tibia using peripheral quantitative computed tomography (pQCT). Surveys were used to assess nutritional intake and physical activity during the week coinciding with baseline testing. Sport-related lower limb injuries were surveyed

retrospectively for two years at baseline, and then tracked for a 12 month period prospectively. Receiver operating characteristic (ROC) curves were used to establish the predictive ability of baseline measures with prospective lower limb injury in the gymnasts and track and field athletes. An appropriate predictive cutoff value for predictor variables was also established using the ROC curve analysis output. Further logistic regression analysis investigated the predictive ability of musculoskeletal stiffness measures on prospective injury. Logistic regression models were successfully able to predict between 69.2 and 87.2% of prospective injuries from MSS measures. It was concluded that measures of MSS are good predictors of injury in high level adolescent female athletes from high-impact sports.

8.2 Introduction

Sports participation during adolescence has the potential for many positive short and long-term outcomes. For the high level adolescent female athlete however, the increased demands of training and competition during a time of critical growth, also has the potential for increased injury risk (Purnell et al., 2010). Adolescent athletes involved in high-impact sports, such as gymnastics and track and field, may be at greater risk of stress-related injury irrespective of age and training hours (Loud et al., 2005). Measures of musculoskeletal stiffness (MSS) attempt to quantify how an athlete attenuates forces during ground contact (impact), and may provide the link between increased injury risk and loading in high-impact adolescent athletes.

Adolescent athletes involved in gymnastics and track and field experience a high number of musculoskeletal injuries (Sands et al., 1993; Zemper, 2005). Within Australian track and field athletes, load-related injuries and hamstring strain are among the most commonly reported injuries (Bennell & Crossley, 1996). Ankle and knee injuries are reported as common injuries in high-level gymnasts (Kirialanis et al., 2003). Particularly in load-related injuries such as stress fracture, a number of potential risk factors in athletic female populations are suggested. These include menstrual factors, nutrition (e.g. low calcium intake), training hours, site specific markers of bone health and anthropometric measures (Bennell et al., 1999).

For the high level adolescent athlete, increased exposure to training and competition loads during maturation may place them at greater load-related injury risk (Maffuli et al., 2005; Loud et al., 2005). Increases in training volume have also been related to an increased risk of lower limb soft-tissue injuries in runners (Yeung & Yeung, 2001). However, the magnitude of the loading experienced (i.e. training intensity) may be more critical in stress related injury than an increase in loading volume (Edwards et al., 2010). An understanding of the nature of the loading experienced and its impact on the growing musculoskeletal system may provide key insights for injury prevention (Sands, 2000). Measures of MSS may provide such a measure.

Differences in lower limb MSS have been linked with increased injury risk (Butler et al., 2003). It was suggested that higher levels of MSS may influence overuse injuries by increasing peak forces and loading rates (Butler et al., 2003). Greater levels of stiffness were found among high-arched runners who had retrospectively experienced a higher number of bony injuries (Williams et al., 2001, 2003). The same series of studies found that low-arched runners had less MSS and experienced a higher incidence of soft-tissue injuries. It was suggested less stiffness was connected with undesirable increased ranges of motion, adding extra stress to the soft-tissues.

Reduced stiffness has also been implicated as a potential factor in the increased incidence of ACL injuries observed in female athletes (Granata et al., 2002b). A retrospective investigation into MSS and ankle injury, found a potential 'safe' stiffness zone (Bradshaw et al., 2006). Gymnastics who exhibited levels of MSS above the 'safe' zone during a continuous straight-leg jump task had experienced previous ankle take-off injuries. The one athlete who presented below the safe stiffness zone had experienced an ankle injury during landing. It was suggested that the take-off injuries resulted from the increased loading associated with higher levels of stiffness and that the landing injury may have been influenced by increased collapse of the joint due to lower MSS levels.

Although it would appear that MSS and injury are associated, few studies have longitudinally investigated the impact of MSS on injury. Only recently a prospective study suggested support for the link between measures of MSS and increased injury risk in elite Australian Rules footballers (Watsford et al., 2010). The results of the study indicated significant differences between players with and without hamstring injury in pre-season measures of leg and hamstring stiffness. A potential link between increased levels of musculotendinous stiffness and hamstring injury was proposed, however differences in methodology, relatively low numbers of injuries, and substantial differences in age, previous hamstring injury and potential training history between the injured and non-injured groups may have influenced these results. Further prospective research into the impact of MSS on potential injury-risk is required. Research into prospective injury-risk identification using MSS measures is particularly pertinent for high level adolescent female athlete in whom the interaction of growth and increasing training demands may increase injury risk.

The purpose of this study was to investigate the ability of measures of lower limb MSS to predict lower limb injuries prospectively in adolescent female athletes competing in high-impact sports. It was hypothesised that greater levels of MSS at baseline would predict both overuse injuries and fracture and stress fracture risk. Conversely, it was expected that lower MSS levels would be able to predict acute, soft-tissue injuries within the same athletes.

8.3 Methods

8.3.1 Participants

Eight-three adolescent female athletes from gymnastics, track and field, water polo and a non-sporting group completed both baseline and 12 month testing (Table 8.1). Non-sporting participants were healthy adolescent females who participated in less than four hours of organized sporting activity outside of normal school involvement. All participants were injury free at the time of baseline testing. Participant and parental/guardian consent for participants under 18 years of age was obtained prior to testing. The study was approved by the University Ethics Committee.

8.3.2 Test Procedure

Baseline testing consisted of adolescent females taking part in a series of jump tests to assess lower limb MSS and a tibial bone scan to assess site specific markers of bone health. Participants completed the warm-up, familiarisation and jumps testing as outlined in Chapter 5.

Following the jump testing and bone scan, participants completed a series of self-report questionnaires assessing injury history (Appendix D), maturational (Appendix G) and menstrual status (Appendix H), dietary (Appendix F) and typical training hours. Participants could either complete the surveys at the conclusion of the test session or return the information in a provided reply-paid envelope.

The test sessions corresponded with a major competition for each sporting group to capture a full training year for the athletes.

Following baseline testing, participants were followed up at six-months and 12-months to assess injuries prospectively.

Table 8.1

Participant Age, Height, Body Mass, Nutritional, Training and Maturation Status, Reported as Mean ± Standard Deviation with the Exception of Tanner Pubic Stage, Tanner Breast Stage and Menstruation Status which are Presented as Median values and Ranges.

Group	n	Age (yrs)	Height (cm)	Mass (kg)	Training (hrs/wk)	Caloric Intake (kCal)[a]	Calcium Intake (mg)[b]	Tanner Breast Stage	Tanner Pubic Stage	Menstruation Status	Age First Menstruation
Controls	26	14.4 ± 1.0	163.9 ± 5.8	58.9 ± 9.4	1.0 ± 1.5	2027.3 ± 512.7	1105.1 ± 849.9	3 2 - 5	4 3 – 5	1 1 - 3	12.8 ± 1.4
Water Polo	18	15.9 ± 0.7	170.7 ± 5.1	66.2 ± 8.1	13.0 ± 5.2	2030.4 ± 667.6	810.9 ± 234.3	3 2 – 5	4 3 – 5	1 1 - 2	13.0 ± 1.4
Gymnastics	17	13.5 ± 1.5	145.6 ± 8.2	38.1 ± 6.7	33.6 ± 1.9	1850.4 ± 680.2	972.0 ± 299.5	3 2 – 3	4 2 - 4	0 0 - 2	13.8 ± 3.5
Track & Field	22	15.5 ± 1.1	169.1 ± 7.0	58.0 ± 5.2	7.8 ± 3.1	2139.0 ± 375.8	1026.4 ± 400.0	3 2 - 5	4 2 - 5	1 0 - 2	13.1 ± 1.1

Notes: The recommended daily intake for adolescent females aged 12-18 years in Australia and New Zealand is [a]2245 kCal for caloric intake and [b]1300 mg for calcium intake (http://www.nrv.gov.au). The recommendations are an average and don't account for individual variations in physical activity such as those female athletes engaged in high level training. Menstruation Status; 0 – represents very irregular (more than 2 months apart), 1 – represents a regular menstrual cycle (every 2 months), 2 – represents a very regular menstrual cycle (every month).

8.3.3 Data Collection and Analysis

8.3.3.1 Measures of Musculoskeletal Stiffness

Measures of lower limb MSS were collected and calculated as outlined in Chapter 5.

8.3.3.2 Site Specific Markers of Bone Health

Site specific markers of bone health were obtained using peripheral quantitative computed tomography (pQCT; XCT 2000, Stratec Medizintechnik, Pforzheim, Germany). Participants were seated with their non-dominant tibia placed in the scanner and secured so that movement of the limb was prevented. Participants were instructed to remain as still as possible during the scan. Scans were performed at the 4% and 66% tibia as measured from the anatomic reference line (cortical end plate). Tibial length (mm) was measured externally from the mid-point of the distal medial malleolus to the proximal medial tibial plateau. Trabecular area (mm^2), density (mg/mm^3) and strength strain index (SSI; mm^3) were calculated at the 4% distal tibial site using the standard pQCT software. Corticol bone area, density, SSI and muscle and fat area (mm^2) were calculated at the 66% distal tibial site. The precision of repeat measurements within our department for this equipment is 0.8% to 2.9% for the tibia.

8.3.3.3 Retrospective and Prospective Injury

Retrospective injury was assessed for the preceding two years prior to baseline testing using a self-report questionnaire. An injury was defined as any physical problem as a direct result of participation in their chosen sport or activity, resulting in an athlete missing or modifying a subsequent training session or competition due to the injury (Kirialanis et al.,2003). Information on the type of injury, approximate injury date, any resulting treatment and the impact on training was gathered. Injuries reported that were not directly related to the participants' sport were excluded. Only lower body injuries were included in injury prediction analysis. Injuries were categorised based on three categories; lower body, acute or overuse and fracture. Acute injuries were defined as injuries having a sudden onset, whereas overuse injuries were defined by a gradual onset potentially across multiple training sessions. The fracture category included suspected fracture, stress fracture, stress reaction and suspected stress reaction.

Prospective injury was recorded at six monthly intervals across the 12 month test period using a self-report questionnaire. Injuries were defined as per the retrospective injury analysis. Information regarding injuries that occurred in the previous 6 months was collected. Details regarding the injury type, location, diagnosis (if any), treatment, severity, injury mechanism, and injury nature (new or recurrent injury) were recorded to assist in correct injury classification (Finch, 1997). As per retrospective injury, only sport-related, lower body injuries were included for further analysis. Common chronic injury problems such as Osgood-Schlatters and Severs disease were categorised as overuse injuries (Christopher & Congeni, 2002). A sub-sample of participant injury reports (n = 26) were cross-checked with athlete coaches and parents to verify recall accuracy. Injury records were positively verified in all cases.

Prospective injury frequencies were summarised by injury location which included multiple injuries for any one participant. Ongoing recurrent injuries were only classified as one injury. Prospective injury data was also classified by number of athletes who experienced that injury at some point in time within the 12 month observation period. Athletes were classified as displaying the particular type of injury if one of more injuries of that nature were sustained in the test period.

8.3.3.4 Dietary Intake, Pubertal Assessment and Training Hours

Participants completed a three-day food diary during two weekdays and one weekend day. Total caloric intake (kJ), calcium intake (mg) and macronutrient data were estimated using the Foodworks™ software program (Xyris Software 2007, Version 5.0, Brisbane, Australia). Pubertal status was assessed using a self-reported assessment of Tanner stage for breast and pubic hair development (Duke et al., 1980). Menstrual status included age of menarche and number of menses in the previous 12 months. Menses was coded into three categories; premenarcheal, oligomenorrehic (onset of menarche within the past six months) and eumenorrehic (more than nine cycles a year; Fiesler, 2001). Typical training hours per week were also recorded.

8.3.4 Statistical Analysis

The Statistical Package for Social Sciences (SPSS) version 17.0 was used for statistical analyses with an alpha level set at $p<0.05$. Normality was assessed for each data set prior to analysis using the critical appraisal approach (Peat & Barton, 2005). Data considered non-normal was log-transformed prior to statistical analysis (Atkinson & Nevill, 1998). Analysis of covariance (ANCOVA) controlling for tibial limb length was conducted for comparison of site specific tibial bone health markers.

Similarly, analysis of covariance (ANCOVA) controlling for body mass and jump frequency was conducted for comparison of site specific tibial bone health markers. For the assessment of potential injury risk, only those athletes from high-impact sports were included.

8.3.4.1 Residual Calculations

Musculoskeletal stiffness measures and site specific markers of bone strength were covaried to account for group differences. Both jump frequency and body mass have been shown to influence MSS measures (Farley et al., 1991; Padua et al., 2005). A linear regression was calculated for each separate participant group by predicting each MSS measure using jump frequency, body mass and participant group (Appendix J). These equations were used to calculate the residual value for each participant from the 'expected' for their group, mass and observed jump frequency (Figure 8.1). Finally, this residual was added or subtracted from the predicted stiffness value for their group at a standard jump frequency and body mass, as calculated using the analysis of covariance (ANCOVA) between groups comparison for the same measure. This

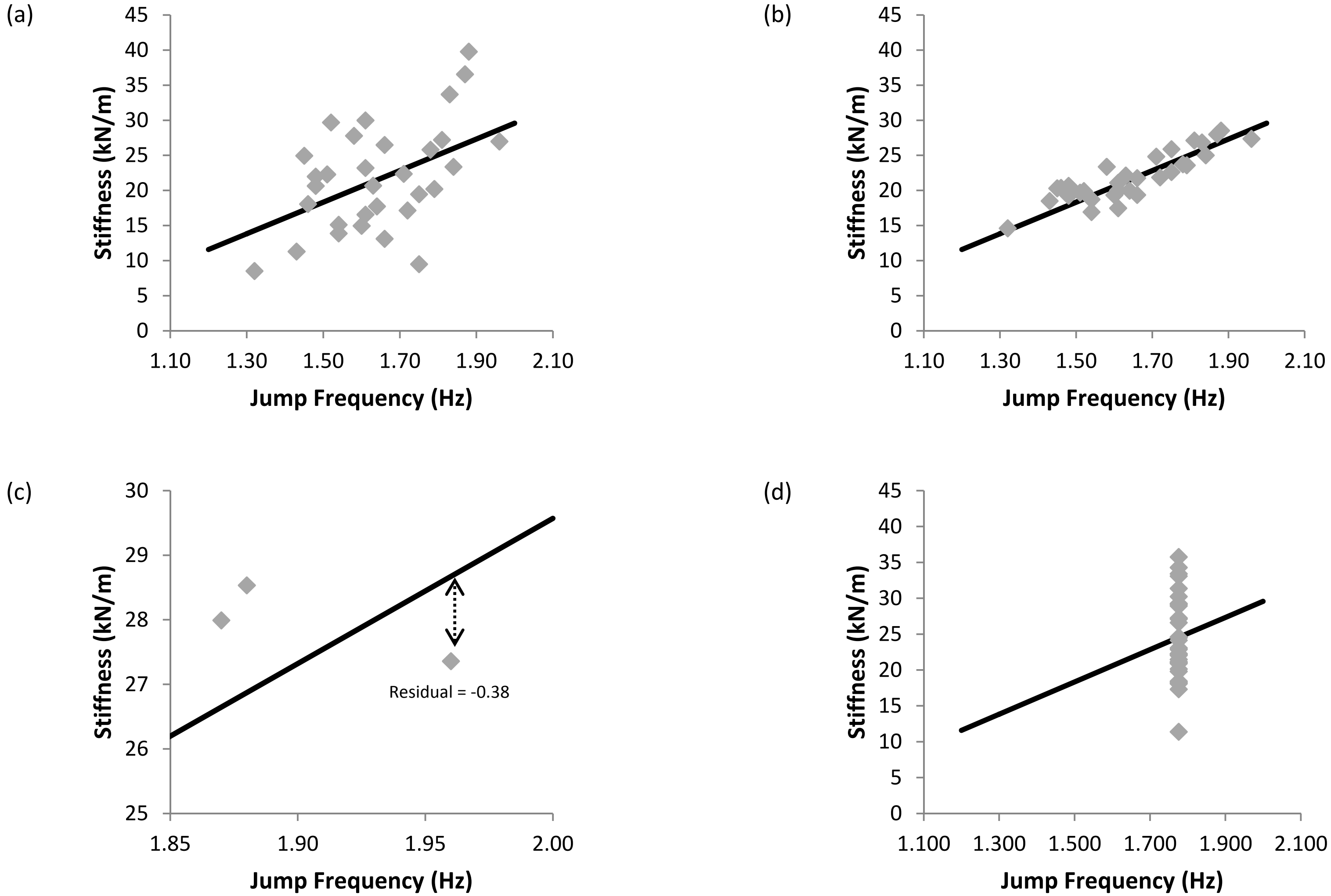


Figure 8.1 Graphical representation of the individual score adjustment for covaried variables for a sample variable; (a) fitting of linear regression model to the stiffness scores based on covariates, (b) scores adjusted using the linear regression equation and observed covariate and raw score, (c) calculation of residual, and (d) 'raw' score offset from 'standard' participant score.

resulted in standardizing the observed individual MSS scores to the same 'typical' body mass and jump frequency.

For the MSS values, standardization was to a 'standard' body mass of 56.43 kg and the following frequencies; CJb 1.401 Hz, CJs 1.776 Hz, CJb30sEarly 1.568 Hz and CJb30sLate 1.668 Hz. Similarly, site specific markers of bone health were standardized to a tibial limb length of 367.1 mm. The 'standardised' scores were then used to identify potential injury prediction in subsequent receiver operating characteristic (ROC) curve and logistic regression analysis.

8.3.4.2 Injury Prediction

Receiver operating characteristic (ROC) curves were calculated to assess the ability to predict injury risk and identify any associated critical threshold value. Each predictor variable was used to separately distinguish four prospective injury classifications; 1. the presence lower limb injury within the 12 month test period, 2. the presence of overuse injury, 3. the presence of acute injury, and 4. the presence of fracture or suspected fracture.

For measures that were considered to reasonably distinguish between injury incidence or absence (i.e. approached significance), the cutoff value for the variable was assessed by exporting the sensitivity and specificity table. Simple trigonometry was used to evaluate the value that was closest to the 'perfect' prediction point (Sensitivity: 1.00,1 – Specificity: 0.00). The calculated cutoff value was used to transpose the variable that was re-coded to reflect participant scores below or above the threshold identified by the ROC curve. Additional variables of a categorical nature were assessed for potential prediction using Chi-square analysis and were included as potential predictor variables in logistic regression if the result approached significance.

A number of variables, such as age, growth and training hours posed difficulties in injury prediction analysis. Due to the large variability between the high-impact groups in these measures, ‘raw’ variables produced significant or not significant results based solely on which group of participants had more of that type of injury. Therefore, a number of variables were normalized to the participant group using z-scores. Adjusted variables were then used in further ROC curve analysis for predictive value.

Following re-coding based on the cut-off value identified by ROC curve and Chi-square analysis, variables which appeared related to increased injury risk were entered into a logistic regression model to evaluate the ability of these factors to predict increased injury risk in high level adolescent athlete populations. Variables were checked for colinearity using a correlation matrix. In addition the change in odds ratio was also assessed to ensure limited relationship between independent variables (Peat & Barton, 2005). Approximately 64% of the high-impact participants (fifteen track and field athletes and nine gymnasts) fully completed and returned the questionnaires resulting in a number of variables being excluded from the logistic regression model due to reduced participant numbers. This included nutritional information, maturation and menstrual status, as well as physical activity.

8.4 Results

8.4.1 Prospective Injury

A summary of the prospective injuries by the number of participants is presented in Table 8.2. Figure 8.2 shows the self-reported prospective injuries by site on the body and frequency. As expected, athletes from high-impact sports experienced a large number of injuries. Only one gymnast failed to record an injury across the 12 month prospective period. Of these recorded injuries, 88% of gymnasts sustained a lower limb injury. Similarly, 64% of track and field athletes experienced a lower limb injury of some kind across 12 months of training. In contrast, only 22.2% of the water polo players experienced a lower limb injury and only one non-sporting participant received a sports-related injury in the 12 month test period.

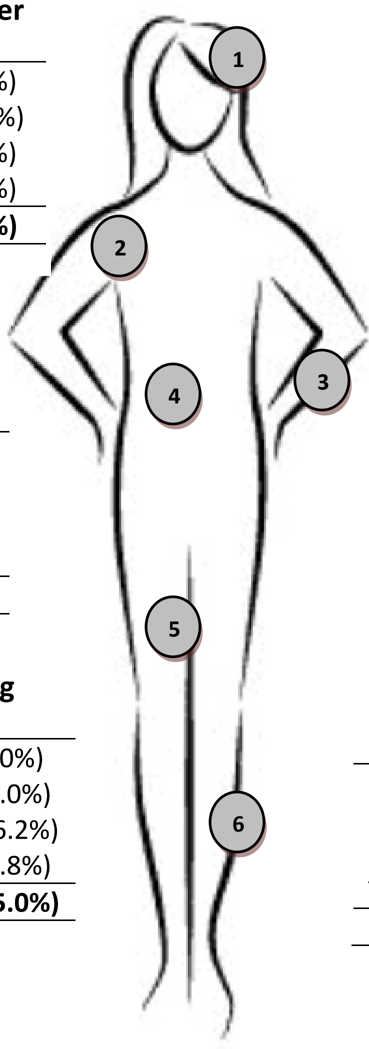
By far the most common injury across the groups was to the lower leg, representing approximately half of all injuries recorded overall. The next highest proportion of injuries was recorded for the knee and upper leg with 25% of all reported injuries occurring at this location. The trunk and lower back was the next most common injury location. A relatively modest number of injuries occurred to the upper body, head and neck across the 12 month period investigated in the present study. The highest number of injuries was recorded in the gymnastics and track and field groups who reported predominantly lower limb injuries with a high proportion at the lower leg, ankle and foot.

Table 8.2

Number of Participants Who Sustained a Prospective Sport-Related Lower Limb Injury during the 12 Month Test Period (Percentage of Participant Group in Brackets).

Group	**n**	**Total Injured**	**LL Injury**	**LL Injury History**		**LL Injury Nature**		**LL Fracture***
				New Injury	Recurrent Injury	Acute	Overuse	
Controls	26	1 (3.8%)	1 (3.8%)	0 (0.0%)	1 (3.8%)	1 (3.8%)	0 (0.0%)	0 (0.0%)
Water polo	18	5 (27.8%)	4 (22.2%)	2 (11.1%)	2 (11.1%)	2 (11.1%)	2 (11.1%)	0 (0.0%)
Gymnastics	17	16 (94.1%)	15 (88.2%)	12 (70.6%)	3 (17.6%)	8 (47.1%)	13 (76.5%)	5 (29.4%)
Track & Field	22	16 (72.7%)	14 (63.6%)	9 (40.9%)	5 (22.7%)	5 (22.7%)	9 (40.9%)	3 (13.6%)
Total	83	38 (45.7%)	34 (40.9%)	23 (27.7%)	11 (13.3%)	16 (19.3%)	24 (28.9%)	8 (9.6%)

Note. Participants were considered either "Yes" or "No" for each category. i.e. more than one injury of the same category did not change the participant count. *This value includes fracture, stress fracture, suspected fracture and suspected stress fracture/stress reactions. LL – lower limb



1. Head & Neck

Control	0 (0%)
Water Polo	0 (0%)
Gymnastics	2 (4.8%)
Track & Field	0 (0.0%)
Total	**2 (2.8%)**

2. Upper Arm & Shoulder

Control	0 (0.0%)
Water Polo	1 (20.0%)
Gymnastics	4 (9.5%)
Track & Field	0 (0.0%)
Total	**5 (6.9%)**

3. Hand, Wrist & Lower Arm

Control	0 (0.0%)
Water Polo	0 (0.0%)
Gymnastics	3 (7.1%)
Track & Field	0 (0.0%)
Total	**3 (4.2%)**

4. Trunk & Back

Control	0 (0.0%)
Water Polo	0 (0.0%)
Gymnastics	5 (11.9%)
Track & Field	4 (16.7%)
Total	**9 (12.5%)**

5. Knee & Upper Leg

Control	0 (0.0%)
Water Polo	2 (40.0%)
Gymnastics	11 (26.2%)
Track & Field	5 (20.8%)
Total	**18 (25.0%)**

6. Foot, Ankle & Lower Leg

Control	1 (100.0%)
Water Polo	2 (40.0%)
Gymnastics	17 (40.5%)
Track & Field	15 (62.5%)
Total	**35 (48.6%)**

Figure 8.2 Number of self-reported prospective injuries by participant group and anatomical location (brackets represents percentage of all injuries sustained for each participant group and overall number of injuries sustained for the 'Total' category).

Note. Summary injuries include multiple injuries which may have been experienced by one athlete

8.4.2 Nutrition, Training Load and Site Specific Markers of Bone Health

Descriptive results for nutritional information and training hours are reported in Table 8.1. Estimated means for site specific markers of bone health following covariance for tibial length are also summarised below in Table 8.3.

Table 8.3

Estimated Mean ± Standard Error for Tibial Site Specific Markers of Bone Health.

Group	**TL* (mm)**	**4% Tibia**			**66% Tibia**				
		TA (mm^2)	TD (mg/cm^3)	TSSI (mm^3)	CA (mm^2)	CD (mg/cm^3)	CSSI (mm^3)	MA (mm^2)	FA (mm^2)
Controls	366 ± 26	501.3 ± 10.8	242.7 ± 9.8	1677.8 ± 92.8	320.8 ± 8.1	1093.5 ± 5.3	2015.3 ± 67.1	6040.4 ± 142.9	2645.8 ± 122.7
Water Polo	381 ± 23	450.2 ± 13.6	236.7 ± 12.3	1627.8 ± 116.0	328.0 ± 10.2	1108.6 ± 6.6	2133.4 ± 83.9	5568.9 ± 178.7	2767.4 ± 154.0
Gymnastics	331 ± 25	510.0 ± 16.1	364.5 ± 14.6	2422.4 ± 137.6	322.3 ± 12.0	1052.8 ± 7.8	2058.1 ± 99.5	5446.6 ± 212.0	1380.1 ± 181.7
Track & Field	381 ± 23	474.1 ± 12.4	300.5 ± 11.2	2193.5 ± 105.8	358.1 ± 9.3	1111.4 ± 6.0	2205.4 ± 76.4	6598.6 ± 162.9	1973.2 ± 142.3

Note. All bone measures were covaried for tibial length; * Non-covaried results thus these values are the mean ± standard deviation; 4%: represents 4% from the distal anatomical reference line; 66%: represents 66% from the distal anatomical reference line. TL: tibial length, TA: trabecular area, TD: trabecular density, TSSI: trabecular strength, CA: cortical area, CD: cortical density, CSSI – cortical strength, MA: muscle area, FA: fat area.

8.4.3 Receiver Operating Characteristic (ROC) Curves

Summary results for the best predictors of lower-limb injury based on receiver operating characteristics curves are contained in Table 8.4. Figure 8.3 shows the ROC curve results for best predictors from the MSS measures. A complete table of ROC curve results is contained in Appendix K.

A reduced average 3-day energy intake appeared to be the best predictor of both general lower limb injury and acute injury with a significant result for prediction area based on ROC curve analysis. Reduced average energy intake was also a significant injury risk predictor in overuse injuries, although it was not as strong as some of the MSS measures for this type of injury.

Of the MSS measures, ROC curve analysis identified a k_{vert} of 12.15 kN/m or above, during the CJb jump task as the best MSS measures to predict general lower limb injury. Similarly k_{vert} was also the best MSS predictor of acute and overuse injuries. A MSS threshold of ‘at or below’ 21.98 kN/m was identified as the best MSS predictor of acute injury however, it was not significant, p = 0.211. In contrast, k_{vert} of 23.05 kN/m or above during the CJs task was found to be highly significant in predicting overuse injury cases, p = 0.006. A reduced change in MSS across the fatigue task (CJb30) was the best MSS predictor measure for fracture risk based on ROC curve analysis.

In addition to the MSS measures, change in height and strength-strain index (SSI) at the 4% distal tibial site were the only other parameters able to significantly predict injury risk in the present study. Despite its apparent ability to correctly predict acute injury, change in height was not entered into the logistic regression model due to the marked differences in this parameter between participant groups.

Table 8.4

Summary of the Best Predictors, Curve Area (Area), Significance (sign.) and Calculated Critical Cutoff Value (Cutoff) with Prospective Injury Measures Based on Receiver Operating Characteristic (ROC) Curve Analysis.

Injury	**Risk factor**	**Area.**	**Sign**	**Cutoff**
Lower Limb	Av Energy	0.889	0.003	9366.5 kCal
	CJb k_{vert}	0.662	0.131	12.15 kN/m
	CJb30 Δk_{conc}*	0.638	0.198	3.59 kN/m
Acute	Av Energy*	0.728	0.071	8081.9 kCal
	Δ Height	0.661	0.104	3.65 cm
	CJs k_{vert}*	0.624	0.211	21.98 kN/m
Overuse	CJs k_{vert}	0.762	0.006	23.05 kN/m
	CJs k_{Fi}	0.749	0.008	22.22 kN/m
	Av Energy*	0.740	0.046	8379.9 kCal
	CJb k_{vert}	0.666	0.079	12.80 kN/m
Fracture	Tibia 4% SSI	0.770	0.020	2322.6 mm^3
	CJb30 Δk_{conc}*	0.730	0.047	3.36 kN/m
	CJb30Early k_{conc}	0.710	0.071	13.41 kN/m

Note. An area of 0.5 represents the same ability as chance to predict a positive or negative outcome. Cotuff value represents the value at which equal to or above that value signifies an increase in injury risk. * Factor is in the reverse direction in the analysis ie. a smaller value or below represents increased injury risk prediction, Av Enegy – average 3-day caloric intake reported from the 3-day food diary, Av CI – average calcium intake reported from the 3-day food diary

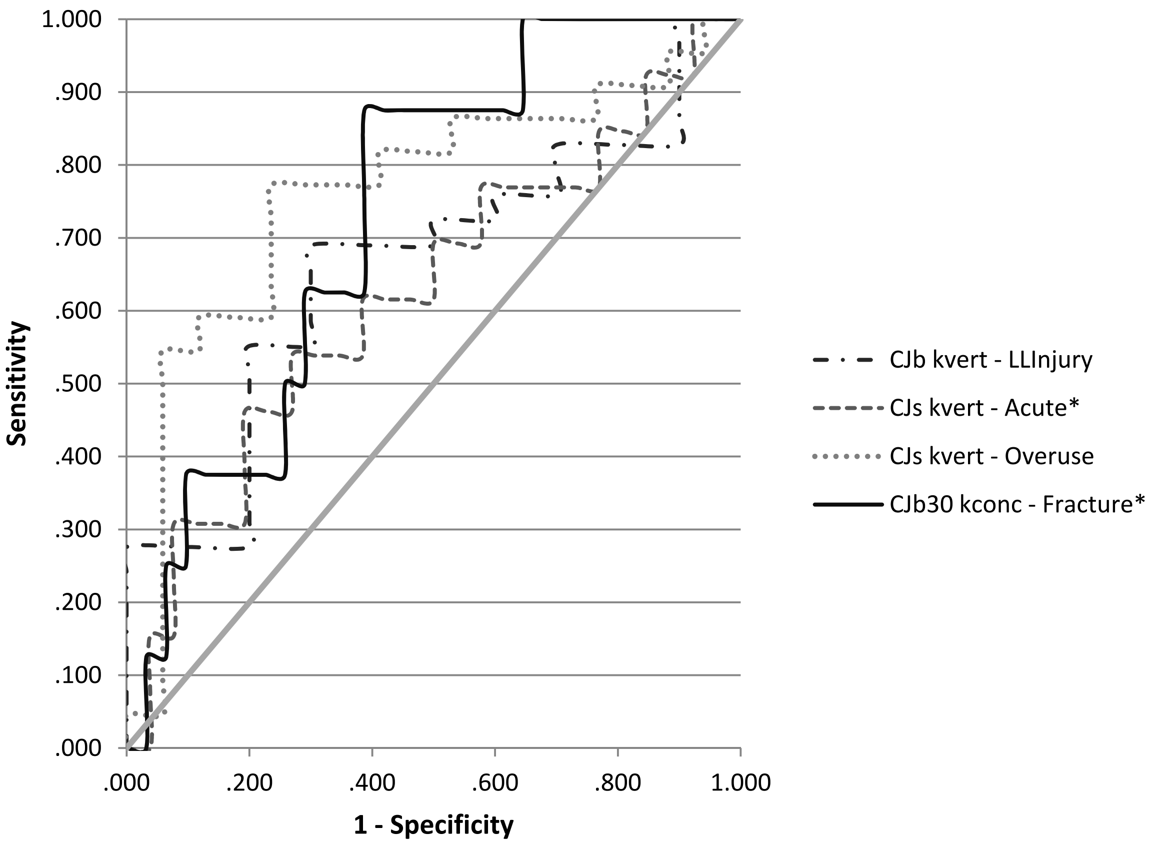


Figure 8.3 Graphical representation of the receiver operating characteristic (ROC) results for the best musculoskeletal stiffness measure predictors of injury.

Note. CJb: continuous bent-knee repeat jumps; CJs: continuous 'straight-leg' repeat jumps; CJb30: continuous bent-knee jumps for 30 seconds; kvert: overall musculoskeletal stiffness measure; kconc: concentric musculoskeletal stiffness measure; LLInjury: prospective lower leg injury; Acute: prospective acute injury; Overuse: prospective overuse injury; Fracture: prospective fracture injury including suspected fracture, stress fracture and suspected stress fracture/reaction; * indicates parameter is reverse coded ie. smaller values represent more positive 'tests'.

8.4.4 Injury Prediction Models

Predictor variables, coefficients, R square values and odds ratios for the prospective prediction of lower limb, acute, overuse and fracture injuries are contained in Table 8.5. In addition, Figure 8.4 shows the numbers of correct and incorrect predictions based on the risk factor and outcome.

Musculoskeletal stiffness during the CJ_b was able to significantly predict 74.4% of general lower limb injuries. The results indicated an increased likelihood of approximately 5.2 times if the lower limb CJb k_{vert} was above a threshold of 12.15 kN/m. Closer inspection of the predicted outcomes (Figure 8.4) suggests increased stiffness appears able to accurately predict lower limb injury but is less accurate in correctly identifying non-injured participants.

Approximately 72% of acute injury classification was correctly predicted using lower scores of CJs k_{vert} and a history of previous acute lower limb injury, although both factors in the model did not reach significance. Appraisal of the outcomes indicated successful identification of uninjured athletes but less accuracy in predicting injured athletes with more incorrect predictions than correct ones for the injured state.

Increased k_{vert} MSS during the CJs suggested approximately 11 times more risk of overuse injury. The significant regression model was able to correctly classify approximately 77% of overuse injury cases. Unlike the previous two models, the prediction of overuse injury based on CJs k_{vert} measures was able to predict both injured and non-injured cases (Figure 8.4).

A lower tibial strength strain index combined with a reduced change in k_{conc} during the CJb30 jump task was able to correctly classify 87.2% of fracture cases. The model found tibial strength to be a significant predictor with the CJb30 measure approaching but not reaching significance. As with overuse injuries, these predictor variables were able to predict both injured and non-injured cases.

Table 8.5

Logistic Regression Model Results and Prediction Equations for the Prospective Explanation of (a) Lower Limb, (b) Acute, (c) Overuse, and (d) Fracture Injuries in High-Impact Athletes.

(a) Lower Limb Injury

Risk Factor	B	SE	Sign.	Odds Ratio	R^2	% correct
CJb k_{vert}	1.646	0.798	0.039	5.185	0.166	74.4
Constant	0.251					

(b) Acute Injury

Risk Factor	B	SE	Sign.	Odds Ratio	R^2	% correct
CJs k_{vert}	1.323	2.994	0.084	3.755	0.212	71.8
Previous Acute Injury	1.875	3.465	0.063	6.523		
Constant	-1.550					

(c) Overuse Injury

Risk Factor	B	SE	Sign.	Odds Ratio	R^2	% correct
CJs k_{vert}	2.402	0.765	0.002	11.050	0.348	76.9
Constant	-0.956					

d) Fracture

Risk Factor	B	SE	Sign.	Odds Ratio	R^2	% correct
ΔCJb30 k_{conc}	2.235	1.185	0.059	9.348	0.423	87.2
Tibia 4% SSI	-2.386	1.179	0.043	0.092		
Constant	-1.994					

Note. B: Beta value; SE: standard error; Sign.: significance value; R^2: Nagelkerke R square value; % correct: percentage of cases correctly identified by the model.

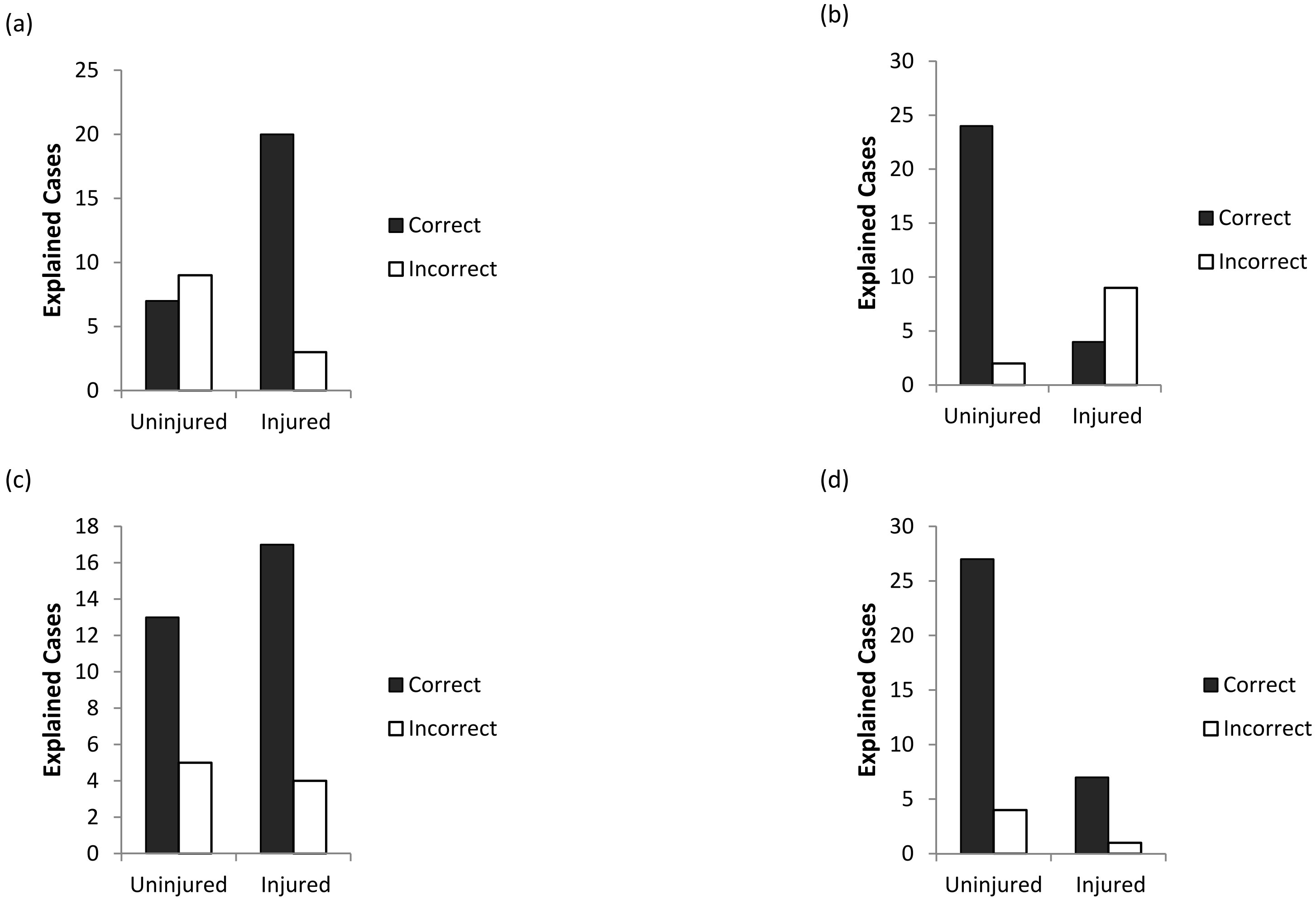


Figure 8.4 Correct and incorrect prediction based on the predictor variables selected for each type of injury category; (a) lower limb injury, (b) acute injury, (c) overuse injury, and (d) fracture.

8.5 Discussion

The results of the present study partially support the hypothesis that greater levels of MSS are related to overuse and stress-related injuries, including fracture and stress fracture. In addition, the results also provide some evidence that lower levels of stiffness are important in acute injury risk.

Measures of lower limb MSS appear to be a good discriminator of overuse injury with high levels of stiffness related to an increase in injury risk. Previous literature implies higher levels of stiffness may place an athlete at increased injury risk due to the increased forces and loading rates on the musculoskeletal system (Butler et al., 2003). Although the underlying mechanisms require further research, the results of the present study add further support to the notion that increased stiffness is related to stress-related injury. The prospective nature of the present study strengthens the evidence for MSS as a potential injury mechanism in the young high-impact athlete.

Measures of MSS during the CJb30s when combined with bone strength at the 4% distal tibia site were able to significantly predict fracture risk in the athletes investigated in the present study. Given the low numbers of fractures reported, some caution should be used in interpreting this result. However, the ability to discern both injured and non-injured athletes based on the predictor variables was promising. Only one fracture case was incorrectly allocated. Thus, it would appear that a reduced increase in MSS during the fatigue trial was associated with an increase in fracture risk. An increase in MSS measures independent of jump frequency during fatigue was postulated to predispose high-impact athletes to increased injury risk (refer to Chapter 6). This would not appear to be supported by the present findings. However, closer inspection of the ROC curve results showed the higher MSS measures during the early contacts of the CJb30 task were also highly related to fracture risk. Thus, the reduced change during the CJb30 task is closely associated with increased levels of MSS across the entire fatigue trial.

Stress fractures result from the inability of the skeletal system to deal with repetitive mechanical loading below the single cycle failure threshold (Brukner & Khan, 1993). Athletes appear more at risk of fracture due increased levels of MSS across the fatigue trial combined with a lower tibia strength index. Although not statistically significant, the results of the present study would also suggest a relationship between lower MSS levels and acute, soft-tissue injury (Bradshaw et al., 2006). Lower MSS during the CJs task appeared adequate in defining the absence of injury however, this measure was not as good at discerning injured athletes. Low levels of MSS may increase the risk of acute soft-tissue injury, but a combination of MSS and other contributing factors may be what eventually result in injury. Although a number of additional factors were investigated in the present study, the relatively small sample size and amalgamation of two distinct sporting populations may have limited the ability to clearly define a multi-factorial model predictive of acute injury risk. The combination of risk factors may be potentially unique to the specific sporting demands. Prospective studies investigating the links between acute injury, stiffness and other potential risk factors within specific populations of athletes may help to identify the potential complex mechanisms underlying acute injury.

As with acute injury identification and MSS measures, general lower limb injury appeared related to higher measures of MSS exhibited during the CJb. Although statistically significant, closer inspection of the data revealed that in general a high level of stiffness appears good at discerning injured athletes. Distinguishing uninjured athletes was not as effective with slightly more predictions incorrect using

CJb stiffness measures. It is possible that a greater level of MSS may be a predisposing factor of lower limb injury. However, it may be too simplistic to generalize this trend to all types of lower limb injury. Although potentially overly simplistic, measures of MSS may remain useful to coaches and athletes as a simple field-based check to indicate athletes who may be ‘at risk’ so that other contributing factors can be more critically appraised and potential injury avoided.

A number of additional potential risk factors were investigated in the present study. Of these factors, ROC curve analysis showed the average energy intake may be highly related to injury in adolescent female athletes. Although detailed discussion of these links is beyond the scope of the present study, abnormal diet, menstrual disturbance and potential osteoporosis are identified as inter-related risks to performance and health, particularly in high level adolescent female athletes (Yeager, Agostini, Nattiv & Drinkwater, 1993). Links between abnormal dietary habits and stress fracture risk have also been established (Bennell et al., 1999). Due to reduced response rates from requests for participants in the present study to complete the three day food diary, average energy was not entered as a factor in any of the logistic regression models. Further investigation into injury models that include MSS and nutritional factors may provide even further ability to identify adolescent athletes at risk of injury.

Training hours have previous been associated with injury in adolescent athletes (Loud et al., 2005). The present study failed to find a significant relationship between training hours and any of the injury measures reported. This finding potentially reinforces the importance of the relative magnitude of the loading not just the volume of loading itself as a potential injury risk in athletic populations (Edwards et al., 2010). However, the combination of two distinct athletic populations and relative differences in training methods, loading and type may have confounded the lack of relationship between training hours and injury risk. Intuitively, the combination of the volume of training load (training hours) and the way an athlete deals with that load (musculoskeletal stiffness) would provide the best reflection of athlete loading and may provide an even better measure of injury risk. Future studies into more accurately and specifically quantifying training volume as well as measures of MSS may be beneficial.

A high incidence of musculoskeletal injuries in high-impact adolescent female athletes has been reported (Sands et al., 1993; Zemper, 2005). Athletes in the present study were no exception, with only one gymnast and six out of 22 track and field athletes not experiencing some form of injury in the present study. Although the overall injuries in the present study appeared similar to previous findings in number and location of lower limb injuries, it would appear that gymnasts experienced more overuse and less acute injuries than in other studies (Kirialanis et al., 2003). The discrepancy in acute and overuse injuries is unclear however; a slight age difference existed between the studies, with the present athletes slightly older. In addition, athletes from the present study were on average completing more training hours (mean: 33.6 ± 1.9 compared with mean: 26.6 ± 3.8) which may explain the difference in injury type. Injuries recorded for the adolescent athletes in the present study appear similar to previous studies into injury rates in Australian track and field athletes (Bennell & Crossley, 1996). The high incidence of self-reported injuries among adolescent athletes in the present study reinforces the need for injury prevention within these athletes.

Limited numbers of injured and uninjured specific cases, particularly with the low number of fracture injuries (n = 8), was problematic in the present study. Low injury incidence may have reduced the effectiveness of the predictor variables. The limitation of low numbers should be noted when interpreting the findings of the present study. Although care was taken to limit the number of risk factors entered into the models based on case numbers, a larger and more homogeneous cohort of adolescent female athletes would provide greater confidence in the outcomes of the results. Investigation into injury risk predictors within high-impact athletes is vital given their apparent injury risk ‘status’. However, specific cohorts of adolescent athletes who can be classified as national or international status, inherently limits the potential participant pool available in relatively small nations such as Australia. Significant efforts were taken to recruit and retain athletes, however the present results are still limited by low case numbers.

Although MSS measures appeared generally effective in their prospective prediction of injury risk in adolescent females, injury risk prediction is based on baseline measures and as such any longitudinal changes in stiffness are not considered in the results. Potential longitudinal changes to stiffness may influence the relationship between the stiffness measures and potential injury risk. However, comparison between baseline and 12 month measures of MSS suggest a moderate relationship between stiffness measures over time with correlation coefficients of 0.61 and 0.62 for CJs k_{vert} and CJs k_{Fi} respectively.

8.6 Conclusion

Specific measures of MSS appear good predictors of lower limb injuries in high level adolescent female athletes involved in high-impact sports. For overuse injuries, increased levels of stiffness appear related to an increased incidence of injury. Similarly, it would appear that high levels of MSS and lower levels of bone strength may increase the risk of fracture, including stress fracture. Lower levels of MSS appear related to increased risk of acute injury although this relationship may be more complex. Athlete screening for MSS measures may allow ‘at risk’ adolescent female athletes to be identified and potential intervention programs implemented.

CHAPTER NINE

Summary

9.1 Overview

Given the high probability of injury associated within high level adolescent female athletes involved in high-impact, high-load sports, injury prevention is of utmost importance. Both short-term and longer-term implications of injury reduction are of significance for high level junior athletes. A better understanding of the mechanisms underlying increased injury risk coupled with the identification of simple measures for early risk detection is vital in potential injury prevention.

Measures of musculoskeletal stiffness (MSS) can quantify the way an athlete deals with force during ground contact. By modelling the muscles, joint and tendons of the lower limb as a simple spring, an objective measure of musculoskeletal response to loading can be obtained. Musculoskeletal stiffness has been linked to performance parameters and injury (Butler et al., 2003). However, a need to validate these relationships prospectively exists. Additionally, the influence of growth and maturation and sport participation on the longitudinal development of MSS in high level adolescent females remains unknown. The longitudinal assessment of MSS and injury within high level adolescent athletes from different populations involving varying degrees of impact and training loading may provide valuable insight into the role MSS plays in sport-specific performance and injury risk.

The present study aimed to;

1. To investigate the impact of a data reduction method on a typical measure of MSS,
2. To investigate the intra and inter-day reliability of selected musculoskeletal measures within an adolescent female population,
3. To investigate potential differences in lower limb MSS between high-impact, low-impact and non-sporting populations,
4. To investigate the relationship between lower limb MSS and the prevalence of injury, particularly specific overuse and 'stress' related type injuries of the lower limb (such as stress reaction, stress fractures, shin splints) in high-impact, high training load adolescent female athletes, and
5. The development of a potential multi-factorial model to predict injury risk in high level adolescent female athletes.

9.1.1 Summary of Hypotheses and Findings

Chapter 4: The impact of data reduction on the intra-trial reliability of a typical measure of lower limb MSS.

Hypothesis (i) *The method of data reduction would have an impact on the intra-trial reliability of a typical measure of lower limb MSS.*

Results supported the hypothesis that the data reduction method selected would have an impact on the intra-trial reliability of MSS measures. Analysis of 'raw' data demonstrated some inherent intra-trial variability within this sample of participants which was substantially reduced by data reduction. Measures of intra-class correlation and coefficient of variation were used to determine differences in variability. Four methods of data reduction were identified as most appropriate within adolescent female athletes and non-athletes.

Chapter 5: The intra-trial and inter-day reliability of lower limb MSS measures in adolescent females.

Hypothesis (ii) *Measures of MSS in adolescent females would be acceptable using the most appropriate data reduction methods.*

Consideration of several measures of reliability was used to evaluate the intra-trial and inter-day reliability of MSS measures, including intra-class correlation, coefficient of variation, percentage bias and Cohen’s effect size. Measures of MSS were considered good to borderline in terms of reliability. Using the most appropriate data reduction method, the MSS measures used in the present study were deemed to have acceptable intra-trial and inter-day reliability.

Hypothesis (iii) *Differences would exist in the intra-trial and inter-day reliability measures based on the data reduction method employed.*

The measures of reliability employed in this chapter supported the hypothesis that the method of data reduction influenced the intra-trial and inter-day reliability of musculoskeletal measures. Intra-trial reliability results indicated a difference between raw scores and different data reduction methods (e.g. CJb k_{vert}: ICC: 0.82 to 0.95; CV%: 9.4 to 16.2). Results also indicated a difference in inter-day reliability based on the data reduction method employed (e.g. CJb k_{vert}: ICC: 0.84 to 0.93; CV%: 9.0 to 13.9).

Chapter 6: Differences in lower limb MSS within high level adolescent female athletes and non-athletes from sports with varied impact loading.

Hypothesis (iv) *Athletes from high-impact sports would show greater levels of jump performance and MSS than low-impact athletes and non-sporting females.*

The hypothesis that greater levels of jump performance and MSS would be present in high level adolescent athletes involved in high-impact sports was supported by the results of this study. Analysis of covariance (ANCOVA) controlling for self-selected jump frequency and body mass results indicated significantly higher stiffness across all jump tasks (e.g. CJb, k_{Fi} T&F: 12.40 kN/m; Gym: 11.80 kN/m; Water Polo: 10.14 kN/m; Controls: 8.04 kN/m). Jump performance was also significantly greater in high-impact athletes. It is postulated that higher levels of stiffness represent more effective utilisation of the elastic properties of the lower limb in high impact sports such as gymnastics and track and field. Greater levels of stiffness may reflect sport-specific adaptations however, a potential genetic component related to an athlete's success in their chosen sport should not be overlooked. Low-impact athletes (in this study, water polo players) showed a somewhat higher level of leg stiffness than non-sporting participants, although this finding was generally not significant.

Hypothesis (v) *High-impact athletes would show minimal changes to MSS under fatigue.*

Using repeated measures analysis of covariance (ANCOVA) results indicated that while high-impact athletes displayed greater general levels of stiffness across a fatigue trial, they showed a greater increase in MSS independent of any changes to jump frequency. This finding was contrary to the proposed hypothesis that they would be able to maintain a similar level of performance and stiffness across the fatigue trial. It was postulated the increase in leg stiffness under fatigue assisted in maintaining performance but may be associated with an increase in injury risk within the high-impact athletes.

Chapter 7: Longitudinal MSS changes in adolescent females from high-impact sporting, low-impact sporting and non-sporting populations.

Hypothesis (vi) *Athletes involved in regular high-impact training would show increases in MSS measures across a 12 month period and that low-impact and non-sporting females would show minimal differences in MSS measures across the test period.*

This hypothesis was partially supported by the results of the present study. Repeated measures analysis of covariance (ANCOVA) results suggested the interaction of sports-specific training, growth and MSS adaptations appears somewhat complex. Longitudinal changes to MSS in the track and field group supported the proposed hypothesis. However, results for the gymnasts failed to indicate an increase in MSS across the 12 month training period. Gymnasts experienced a period of rapid growth across the test period that may possibly 'mask' potential training gains and may warrant consideration from coaches. Despite MSS remaining low relative to the other participant groups, non-sporting participants displayed some increases in MSS longitudinally. Therefore, influences of growth and low-level general activity may have resulted in the subtle increases in stiffness observed in the non-sporting population. Training-induced changes to longitudinal MSS measures may be joint specific. For example, track and field experienced greater increases in CJb stiffness measures than CJs. It is postulated this reflects the greater knee-joint dominance in stiffness adjustment for running. However, joint specific changes and their relationship to sport-specific training and growth require further clarification.

Chapter 8: The development of a kinetic model to prospectively predict increased injury risk in high level adolescent females from high-impact sports.

Hypothesis (vii) *Greater levels of MSS would be associated with overuse and stress-related injuries in high-impact athletes.*

Receiver operating characteristic (ROC) curve analysis and subsequent logistic regression results indicated that greater levels of lower limb MSS appear to be good predictors of prospective injury in high-impact adolescent female athletes. The results revealed that greater stiffness in the CJs task was able to predict overuse injuries within the gymnast and track and field athlete populations. In addition, stiffness measures during the fatigue trial in conjunction with measures of tibial bone strength predicted a relatively high proportion of variability in fracture risk, although the incidence of fracture within the group was not high. The hypothesis that greater levels of stiffness would be associated with stress-related injuries was supported by the findings of this study.

Hypothesis (viii) *Lower levels of MSS would be associated with the incidence of acute injuries in high-impact athletes.*

Although the hypothesis that low levels of MSS would be associated with acute injury incidence was not fully supported in the present study, the results would suggest that this hypothesis is plausible. Logistic regression results suggest stiffness measures from the CJs task appeared able to adequately identify athletes who did not sustain an acute injury. Prediction of injured athletes was not so accurate. Despite acknowledging the prediction of acute injuries in high-impact athletes is multi-factorial, it would appear reduced levels of stiffness are associated with an increase in injury risk.

9.2 Discussion

Collectively, the results support the role of lower limb MSS as an important marker for both jump performance and injury risk within adolescent female athletes. The findings of the present thesis advanced the notion that increased levels of MSS contribute to explosive, dynamic sporting activities (Butler et al., 2003). Arguably more importantly, this research prospectively identifies lower limb MSS as a significant risk factor for injury within high level adolescent female athletes from high-impact sports.

Previous literature has suggested that too little stiffness may place an athlete at increased risk of acute, soft-tissue injuries due to an increase in the range of motion and muscular contribution to performance due to ineffective utilization of the elastic properties of the leg (Bradshaw et al., 2006). Conversely, it's suggested that too much stiffness places an athlete at risk of overuse or stress-related injuries due to the increased force and rate of force transferred to the musculoskeletal system during ground contact (Bradshaw et al., 2006). The present thesis contributes to the literature by comparisons across sports with different weight bearing loads, the use of adolescent females and the longitudinal profile of MSS in performance and injury.

Although the exact mechanisms and contribution of greater stiffness levels remain equivocal, the ability to contact the ground with greater MSS appears an important parameter in successful high-impact sport performance. The ability to effectively use the elastic properties of the leg to maximize efficiency and performance is potentially reflected in high-impact populations in the present study. Longitudinal analysis of MSS changes suggested, at least partially, that the quality of stiffness is related to sport-specific conditioning. However, it must be considered that natural talent and individual genetics may play a role. As simple, field-based measures that could be readily conducted at an external location, the data gathered within this thesis may provide normative data for talent identification purposes within gymnastics and track and field athletes.

Longitudinal comparison of the stiffness measures profiled suggests a complex interaction between growth, training and its subsequent impact on performance, particularly within the gymnasts. The impact of growth on training and competition performance may be something that is ‘under-valued’ by coaches dealing with adolescent athletes. In periods of peak growth, it is possible that training effects may be occurring but in effect are ‘out-paced’ by the physical changes of maturation. Hypothetically, this may result in a potential situation in which, despite appropriate training and loading, relative performance variables fail to indicate a training effect. In the face of less than expected performance results, a coach may conclude the training has not been effective and may prescribe increased loading or a different type of training. The appropriate training response may well be present, but this response fails to impact on the athlete’s performance because the rate of growth has exceeded the effects of training. A response to increase training load may in fact further compromise an athlete who is already vulnerable to injury due to the accelerated growth they experience. Greater focus on athlete longevity (staying healthy and in the sport) and medium- to long-term competition goals is arguably required.

The importance of understanding the potential impact of growth and maturation on performance and underlying performance parameters on the adolescent athlete should not be understated within the coaching and conditioning community. The objective assessment of appropriate growth related measures during the critical years of adolescence would provide the coach with the appropriate information on the potential impact of growth on training adaption. A strategy as simple as regular measurement of standing height and body mass to assess individual athlete growth velocity curves may provide a coach with enough additional information to appropriately prescribe training during a growth spurt and potentially avoid injury during this critical time sports participation.

Globally, benchmarks for injury potential and even talent identification in sport are constantly being explored. Musculoskeletal stiffness results from test sessions within gymnasts and track and field athletes could be expanded following the findings of this thesis. Future athlete screening utilising similar methodology and jump surfaces could compare athlete results with injury risk values identified in this study using the linear regression equations produced (see Appendix J) to evaluate potential injury risk.

When considering the respective jump tasks it would appear that each has a place in a comprehensive overview of lower limb musculoskeletal in adolescent athletes. The CJb jump task appears a good indicator of longitudinal change to MSS among track and field athletes and water polo payers. Sports involving high levels of running and sprinting or with an increased dominance on the knee or thigh musculature may benefit from using this CJb test to discriminate potential stiffness changes. In contrast, sports involving a series of fast, repeat contacts, such as gymnastics, the more ankle-dominated CJs may be more appropriate. The CJs jump task appeared to be the best discriminator of stiffness differences and injury risk among the athletes tested in the present study. Based on reliability results and its ability to discriminate overuse and acute injury the CJs jump task appears a good test of lower limb stiffness within adolescent female populations. The fatigue task appears to be the preferred jump task when considering fracture risk.

Although the findings of the present study are confined to specific sporting populations, it is suggested that the general patterns of results may be applicable to other sporting populations who are considered high or low-impact in nature. Because the project recruited adolescent females from a range of sporting populations and backgrounds, the results of this study may be more generalizable to the wider sporting population. Specific studies into normative levels and specific 'at risk' groups and stiffness levels within other sporting or non-sporting populations would be required to provide a valid tool for identifying injury risk in other sporting populations.

9.2.1 Strengths

- The longitudinal assessment of differences and changes to lower limb MSS, particularly within the adolescent athlete, allows a unique insight into the nature of growth, sports-specific training, MSS qualities and jump performance.

- A prospective approach to the prediction of injury using measures of MSS extends the knowledge and evidence for the links between MSS, performance and injury risk.

- Previous research in MSS has typically used participants of similar stature and sport. The use of distinctly different sporting populations in the present study offered unique opportunities and challenges. The use of generic stiffness measures allowed comparison of MSS across a spectrum of weight bearing activity levels among the adolescent female population and provided different insights into the role of lower limb stiffness in athletic performance.

- Statistically, controlling for variations in self-selected jump frequency in the present study was novel in stiffness research. By allowing participants to self-select their preferred jump frequency and subsequent stiffness profiles, it is believed that the observed stiffness characteristics may be more representative of participants' chosen stiffness characteristics in their sport.

- The use of simple, field-based jump measures and portable force plates means the test measures and results of the present thesis could be accessible for talent identification or injury risk screening purposes.

- Finally, the advancement of knowledge into the potential risk factors and the possibility of identifying potential athletes 'at risk' remains an important outcome. High level adolescent athletes are vulnerable to increased injury risk which may have short and longer-term health implications. The ability to adequately identify risk factors is relevant for future injury prevention strategies and programs.

9.2.2 Weaknesses

- A convenient sample of participants represented each of the four groups in this study, and as such may have represented some degree of bias. Sporting participants in the present study were also recruited at a relatively high level of competition. Potential influences on results such as training programs and schedules, recovery, nutritional practices, competition schedules and extra-curricular activity were beyond the control of researchers.

- Retention of participants is always a challenge in longitudinal studies, particularly involving young athletes from vastly different sports. Although a reasonable number of participants completed the 12month testing, reduced participant numbers, particularly for injury risk analysis, was a challenge.

- Although tests were selected based on their functional relevance to the underlying requirements of high-impact sports, the test measures used in the present study were generic and as such may not fully reflect the musculoskeletal properties evident in an applied sporting situation.

- Despite the best efforts of researchers to obtain complete questionnaires on maturation, nutrition and training activity, full data sets for all participants were not obtained. The lack of complete data sets placed limitations on the interpretation of results from potential influences on MSS change and injury risk.

- Despite participants being injury-free at the commencement of testing and self-report questionnaires suggesting a majority of new prospective injuries were reported among participants (67.6% compared with 12.7% recurring injuries), previous injury history and injury type may have influenced the results of the present study.

9.2.3 Recommendations and Future Directions

- The regular monitoring of MSS may be useful in tracking potential training adaptations within high-impact athletes. Such measures may be useful in evaluating some of the underlying mechanisms of performance and how specific training interventions influence these parameters.

- The impact of growth during adolescence should be an important consideration for coaches and trainers of young female athletes. Training adaptations should be evaluated in conjunction with potential growth to ensure an accurate appraisal of change is made. Poor or reduced relative performance following sport-specific training may not necessarily reflect a failure to appropriately adapt. Particularly within high-impact, adolescent female athletes, the influence of growth on performance outcomes should be considered in training programming decisions. It is recommended that the collection of appropriate growth related measures be considered by coaches and trainers of adolescent athletes. However, confidentiality and privacy issues around measuring body mass in young females should be given equal consideration.

- Further investigation into the relationships between growth, training adaptations and musculoskeletal measures may be of benefit in providing more clarity to the interaction between these measures.

- Mechanisms of change, including the potential influence of growth on self-selected jump frequency, underlying longitudinal MSS differences may provide greater insight into the influence of growth and sport-specific training on stiffness.

- Pre-season or annual screening of gymnasts and track and field athletes using similar musculoskeletal measures and equipment (particularly the jump surface) to those employed in the present study may assist in identifying lower limb injury 'at risk' athletes. Close monitoring of training load, recovery practices and injury symptoms of those identified as 'at risk' may assist in the early detection and possible prevention of overuse injury.

- Arguably, the ability to turn injury risk assessment into injury prevention is the major aim of all applied injury research. Investigation into the effectiveness of preventative measures for 'at risk' athletes identified using the musculoskeletal measures may further enhance the understanding of the role of MSS. Equally this assessment of injury risk may potentially go some way to reducing the incidence of injury among this critical population of aspiring athletes

- Prospective studies involving larger cohorts of adolescent and adult athletes across different sports would strengthen the evidence base concerning the potential ability of stiffness measures to predict lower limb injury.

- Identification of appropriate measures that can quantify MSS and relative loading during the sport-specific tasks may provide even better assessment of potential performance and injury risk capabilities of such measures.

9.3 Conclusion

The period of adolescence is a critical time in an aspiring athlete's career. During adolescence increasing training and performance demands correspond with a period of immense growth and maturation. There is a salient need for sound management and guidance of the young athlete through this stage of their career. In particular, injury prevention in high-impact sports such as gymnastics and track and field is vital for the long-term health and development of the athlete. Lower limb musculoskeletal stiffness appears an important component in both performance and injury risk in talented adolescent female athletes from high-impact sports. Stiffness measures may prove valuable in identifying 'at risk' athletes.

The interaction between sport-specific training, growth and musculoskeletal stiffness development appears complex. Although developments in musculoskeletal stiffness appear related to training for high-impact sports, coaches should be cognisant of the potential impact of growth on relative performance and trainability. An appreciation of growth may assist in appropriately evaluating and assigning training loads.

Finally, measures of musculoskeletal stiffness appear to be suitable measures for identifying athletes at increased risk of injury, particularly stress-related injury. Pre-season screening of athletes may assist coaches and sporting organisations in identifying ‘at risk’ athletes. This may allow closer scrutiny of additional injury risk factors, including day-to-day training loading and potential injury warning signs. Ultimately, injury prevention is the optimal outcome for the high level adolescent female athlete. Although more research is needed, it is hoped the finding of the present theses may go at least some way in assisting in advancing injury prevention in adolescent athletes.

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Appendix A: Ethics Approval Letter

Australian Catholic University
Brisbane Sydney Canberra Ballarat Melbourne

ACU National

Human Research Ethics Committee

Committee Approval Form

Principal Investigator/Supervisor: A/prof Elizabeth Bradshaw Melbourne Campus
Co-Investigators: A/Prof Geraldine Naughton Sydney Campus
Student Researcher: Mr Mark Moresi Sydney Campus

Ethics approval has been granted for the following project:
The use of biomechanics in developing a model to predict performance and injury risk prospectively in adolescent female athletes

for the period: 5th September 2007 - 31st December 2009 (subject to annual renewal)

Human Research Ethics Committee (HREC) Register Number: V200607 87

The following standard conditions as stipulated in the *National Statement on Ethical Conduct in Research Involving Humans* (1999) 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: ....
(Research Services Officer, Melbourne Campus)

(Committee Approval.dot @ 31/10/06) Page 1 of 1

Appendix B: Information Letter and Informed Consent Forms for Participants

ACU National
Australian Catholic University
Brisbane Sydney Canberra Ballarat Melbourne

Australian Catholic University Limited
ABN 15 050 192 660
Strathfield Campus (Mount Saint Mary)
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New South Wales 2135 Australia
Locked Bag 2002 Strathfield
New South Wales 2135 Australia
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INFORMATION LETTER TO PARTICIPANTS

TITLE OF PROJECT: THE RELIABILITY OF FORCE PLATE MEASURES FOR LOWER LIMB STIFFNESS IN ADOLESCENT FEMALE ATHLETES – A PRELIMINARY STUDY

SUPERVISORS: DR ELIZABETH BRADSHAW, DR DAVID GREENE & ASSOCIATE PROFESSOR GERALDINE NAUGHTON

STUDENT RESEARCHER: MR MARK MORESI

ENROLLMENT PROGRAMME: DOCTOR OF PHILOSOPHY (PhD) – EXERCISE SCIENCE

Dear Participant

You are invited to take part in a preliminary study to determine the reliability of a series of biomechanical force plate measures designed to evaluate the ability of the leg to deal with ground reaction forces during jumping tasks.

The study will involve two repeated test sessions, approximately one week apart. You will be asked to complete a series of jumping tasks on two portable force plates, which measure the ground reaction forces throughout each jump.
The jumping tasks to be conducted are:

- a double leg landing task from three set heights,
- double and single leg rebound jumps from three set heights,
- standing long jump for distance,
- rebound long jump for distance,
- double and single leg repeated jumps, and
- single leg repeated jumps for 30 seconds.

Testing should take a maximum of one and a half hours per session, including warm-up time.

As a participant you will receive access to sport science testing which will provide feedback on your current levels of strength and power.

You should note that you are free to choose not to take part in the study and to withdraw from the study at any time without providing a reason. Withdrawal will in no way impact on

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your training or inclusion in any state, national, emerging athlete or institute/academy squads.

The test results from the data collected from you during the study will remain within the confidence of the researchers. Reports will not identify individual participants and only group results will be made available. Group results will be published in scientific journals and presented at scientific conferences. Data will be securely kept within the School of Exercise Science office at the Australian Catholic University, Strathfield, NSW.

Any questions about the above information can be obtained by contacting Dr Elizabeth (Liz) Bradshaw on (03) 9953 3030, email: elizabeth.bradshaw@ acu.edu.au, Associate Professor Geraldine (Jeri) Naughton on (02) 9701 4051, email: g.naughton@mackillop.acu.edu.au, or by regular mail at Australian Catholic University, School of Exercise Science, Locked Bag 2002, Strathfield, NSW 2135.

In the event that you have any complaints or concerns about the way you have been treated by researchers in this study or if you have any query that the researcher has not been able to satisfy, you may write to the Chair of the Human Research Ethics Committee at the following address:

Chair, HREC
C/o Research Services
Australian Catholic University
Melbourne Campus
Locked Bag 4115
FITZROY VIC 3065
Tel: 03 9953 3158
Fax: 03 9953 3315

Any complaint or concern will be treated in confidence and fully investigated. The participant will be informed of the outcome.

If you agree to participate in the study you should sign both copies of the Consent Form, retain one copy for your records and return the other to School of Exercise Science, marked to the attention of Mr Mark Moresi.

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INFORMATION LETTER TO PARENTS

TITLE OF PROJECT: THE RELIABILITY OF FORCE PLATE MEASURES FOR LOWER LIMB STIFFNESS IN ADOLESCENT FEMALE ATHLETES – A PRELIMINARY STUDY

SUPERVISORS: DR ELIZABETH BRADSHAW, DR DAVID GREENE & ASSOCIATE PROFESSOR GERALDINE NAUGHTON

STUDENT RESEARCHER: MR MARK MORESI

ENROLLMENT PROGRAMME: DOCTOR OF PHILOSOPHY (PhD) – EXERCISE SCIENCE

Dear Parent,

Your daughter is invited to take part in a preliminary study to determine the reliability of a series of biomechanical force plate measures designed to evaluate the ability of the leg to deal with ground reaction forces during jumping tasks.

The study will involve two repeated test sessions, one day apart. Testing should take approximately one and a half hours, including warm-up time.

Participants will be asked to complete a series of jumping tasks on two portable force plates, which measure the ground reaction forces throughout each jump.
The jumping tasks to be conducted are:

- a double leg landing task from a set height,
- double and single leg rebound jumps from three set heights,
- standing long jump for distance,
- rebound long jump for distance,
- double and single leg repeated jumps, and
- single leg repeated jumps for 30 seconds.

As a participant your daughter will receive access to sport science testing which will provide feedback on her current levels of strength and power.

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You should note that your daughter is free to choose not to take part in the study and to withdraw from the study, at any time without providing a reason. Withdrawal will in no way impact on her training or inclusion in any state, national, emerging athlete or institute/academy squads.

Your daughters test results from the data collected during the study will remain within the confidence of the researchers. Reports will not identify individual participants and only group results will be made available. Group results will be published in scientific journals and presented at scientific conferences. All data will be securely kept within the School of Exercise Science office at the Australian Catholic University, Strathfield, NSW.

Any questions about the above information can be obtained by contacting Dr Elizabeth (Liz) Bradshaw on (03) 9953 3030, email: elizabeth.bradshaw@acu.edu.au, Associate Professor Geraldine (Jeri) Naughton on (02) 9701 4051, email: g.naughton@mackillop.acu.edu.au, or by regular mail at Australian Catholic University, School of Exercise Science, Locked Bag 2002, Strathfield, NSW 2135.

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PARENT/GUARDIAN CONSENT FORM
Copy for Researcher

TITLE OF PROJECT: THE RELIABILITY OF FORCE PLATE MEASURES FOR LOWER LIMB STIFFNESS IN ADOLESCENT FEMALE ATHLETES – A PRELIMINARY STUDY

SUPERVISORS: DR ELIZABETH BRADSHAW, DR DAVID GREENE & ASSOCIATE PROFESSOR GERALDINE NAUGHTON

STUDENT RESEARCHER: MR MARK MORESI

I ……………..……….....………..(name of parent / guardian) have read the details of the study involving the reliability of force plate measures for jumping tasks (or, where appropriate, have had read to me). I understand that data will be collected on two subsequent test days and will involve ground reaction force measures for a series of jumping tasks. I am aware that group results may be published in scientific journals and presented at conferences. I understand the information provided in the Letter to Participants. Any questions I have asked have been answered to my satisfaction.

I agree that my child, nominated below, may participate in the jumping tasks and force plate measures as outlined in the information letter, realising that I can withdraw my consent at any time without comment or penalty.

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: ....
(block letters)

NAME OF CHILD ....
(block letters)

SIGNATURE .... DATE........./............/...............

SIGNATURE OF SUPERVISORS:

....DATE:....../....../.........
Dr ELIZABETH BRADSHAW

....DATE:....../....../.........
Associate Professor GERALDINE NAUGHTON

....DATE:....../....../.........
Dr DAVID GREENE

SIGNATURE OF STUDENT RESEARCHER:

....DATE: ..../.........../..................
Mr MARK MORESI

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ASSENT OF PARTICIPANTS AGED UNDER 18 YEARS
Copy for Researcher

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 take part in the project, realising that I can withdraw at any time without having to give a reason for my decision. By signing below, you are indicating that you agree to participate in the project.

NAME OF PARTICIPANT AGED UNDER 18: ....
(block letters)

SIGNATURE ....DATE……………/……………/………....

SIGNATURE OF SUPERVISORS:

……………………………………………………………………………DATE:……/……/………
Dr ELIZABETH BRADSHAW

……………………………………………………………………………DATE:……/……/………
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SIGNATURE OF STUDENT RESEARCHER:

………………………………………………………………DATE: …………/…………/………………
Mr MARK MORESI

CRICOS registered provider:
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NAME OF PARENT/GUARDIAN: ....
(block letters)

NAME OF CHILD ....
(block letters)

SIGNATURE .... DATE........../............../...............

CRICOS registered provider:
00004G, 00112C, 00873F, 00885B

SIGNATURE OF SUPERVISORS:

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INFORMATION LETTER TO PARTICIPANTS

TITLE OF PROJECT: THE USE OF BIOMECHANICS IN DEVELOPING A MODEL TO PREDICT PERFORMANCE AND INJURY RISK PROSPECTIVELY IN ADOLESCENT FEMALE ATHLETES.

SUPERVISORS: DR ELIZABETH BRADSHAW, DR DAVID GREENE & ASSOCIATE PROFESSOR GERALDINE NAUGHTON

STUDENT RESEARCHER: MR MARK MORESI

ENROLLMENT PROGRAMME: DOCTOR OF PHILOSOPHY (PhD) – EXERCISE SCIENCE

Dear Participant

You are invited to take part in a study which aims to understand more about factors, predominantly biomechanical, that predict injury risk and performance in adolescent female athletes.

Participants in the project must be female, and aged between 12-18 years. Females and will be drawn from four sub-populations; three athletic populations, track and field, gymnasts, and water polo, and an age-matched sample of females participating in less than four hours of organised sporting activity outside of school per week.

You will be assessed three times throughout the 12-month study period (baseline, 6-months & 12-months). Each individual test session will require a once only visit of approximately two hours. Testing will take place at a venue convenient to your school or training location. At each session the following tests will be conducted:

- Anthropometry measures - standing height and weight will be measured along with some general body dimension measures such as lower limb length, hip and shoulder width and girths. This component of testing is expected to take about 15 minutes.
- Bone density scan – the bone scanner used in this project is called a peripheral quantitative computered tomography (pQCT) scanner. It is a *completely painless* procedure whereby a scan is taken of your lower leg and wrist. While the device contains ionizing radiation, the radiation exposure is extremely small (ie: less than 2 µ Sv per scan). A normal chest x-ray contains 50 µ Sv, while a return transatlantic flight exposes travellers to 80 µ Sv. Scanning is expected to take about 20 minutes.

- Nutritional analyses - dietary calcium (mg) and energy intake (kJ) will be determined using a 3-day (two week days and one weekend day) food diary. Instructions regarding completion of the 3-day food diary will be provided as well as self-addressed stamped envelopes to assist in the return of completed diaries. Your daughter will need to take the diary home to complete.
- Physical activity - physical activity levels will be assessed using a 3-day Physical Activity Record (two week days and one weekend day). Activities will be ranked on a scale from 1 to 9 according to energy expenditure with the least vigorous activity scoring 1 and the most vigorous activity scoring 9. Activity level will be recorded every 15 minutes for three, 24 hour periods. Again, instructions regarding completion of the 3-day physical activity diary will be provided as well as self-addressed stamped envelopes to assist in the return of completed diaries.
- Maturation - you will be asked to complete a self-reported pubertal status questionnaire for pubic hair and breast development. Pubertal status will be determined by your child viewing illustrations depicting the five stages of breast and pubic hair development, as described by Tanner (1962). Participants will be instructed to select an illustration comparable with their own breast size and an illustration comparable with pubic hair development. You will be provided with a private area to complete the self-reported pubertal status questionnaire and can choose to complete the questionnaire with or without parental assistance. This task should take around two minutes to complete.
- Sporting injury history – at the initial visit only, you will be asked to complete a "previous 2-years" sporting injury history questionnaire. This questionnaire should take around 10 minutes. For the two subsequent sessions you will be asked to complete a sporting injury questionnaire for the past 6 month period. Again, this questionnaire should take no longer than 10 minutes.
- Force plate jumping tasks – a series of jumping tasks completed on two force plates, which measure ground reaction forces. Jumping tasks include landing and rebound jumps from a set height, double and single leg repeated jumps, and single leg repeated jumps for 30 seconds. The jumping component of the testing will take approximately 40 minutes.
- Physical response to stress questionnaire – participants will be asked to complete a retrospective questionnaire. Items regarding physical state and attitude towards activity will be assessed. Questionnaires will be kept confidential at all times. This questionnaire takes adolescents around 15 minutes to complete.

The study exposes you to ionizing radiation however, the effective radiation dose from pQCT is extremely small, as outlined above.

As a participant, you will receive regular access to sport science testing and results which will provide feedback on your current levels of strength and power and how this relates to your sport. Six-monthly testing will also enable you the opportunity to evaluate your training progress across the test period. At the conclusion of the study, you will receive a summary report containing information about bone density, bone strength, bone size, dietary calcium and macro-nutrient intake (carbohydrates, fats, protein), anthropometry and force production capacity. Completion of all tests and questionnaires will not have any cost to you.

You should note that you are free to choose not to take part in the study and to withdraw from the study, at any time without providing a reason and with no penalty. Withdrawal will in no way impact on your training or inclusion in any state, national, emerging athlete or institute/academy squads.

Data collected during the study will remain within the confidence of the researchers. Reports will not identify you in any way and only group results will be made available. Group results will be published in scientific journals and presented at scientific conferences. Data will be securely kept within the School of Exercise Science office at the Australian Catholic University, Strathfield, NSW.

Any questions about the above information can be obtained by contacting Dr Elizabeth (Liz) Bradshaw on (03) 9953 3030, email: Elizabeth.Bradshaw@acu.edu.au, Associate Professor Geraldine (Jeri) Naughton on (02) 9701 4051, email: g.naughton@mackillop.acu.edu.au or by regular mail at Australian Catholic University, School of Exercise Science, Locked Bag 2002, Strathfield, NSW 2135.

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INFORMATION LETTER TO PARENTS

TITLE OF PROJECT: THE USE OF BIOMECHANICS IN DEVELOPING A MODEL TO PREDICT PERFORMANCE AND INJURY RISK PROSPECTIVELY IN ADOLESCENT FEMALE ATHLETES.

SUPERVISORS: DR ELIZABETH BRADSHAW, DR DAVID GREENE & ASSOCIATE PROFESSOR GERALDINE NAUGHTON

STUDENT RESEARCHER: MR MARK MORESI

ENROLLMENT PROGRAMME: DOCTOR OF PHILOSOPHY (PhD) – EXERCISE SCIENCE

Dear Parent,

Your daughter is invited to take part in a study which aims to understand more about factors, predominantly biomechanical, that predict injury risk and performance in adolescent female athletes.

Participants in the project must be female, and aged between 12-18 years. Females and will be drawn from four sub-populations; three athletic populations, track and field, gymnasts, and water polo, and an age-matched sample of females participating in less than four hours of organised sporting activity outside of school per week.

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The study exposes your daughter to ionizing radiation however, the effective radiation dose from pQCT is extremely small, as outlined above.

As a participant, your daughter will receive regular access to sport science testing and results which will provide feedback on your current levels of strength and power and how this relates to their sport. Six-monthly testing will also enable you the opportunity to evaluate your training progress across the test period. At the conclusion of the study, your daughter will receive a summary report containing information about bone density, bone strength, bone size, dietary calcium and macro-nutrient intake (carbohydrates, fats, protein), anthropometry and force production capacity. Completion of all tests and questionnaires will not have any cost to you.

You should note that your daughter is free to choose not to take part in the study and to withdraw from the study, at any time without providing a reason and with no penalty. Withdrawal will in no way impact on your training or inclusion in any state, national, emerging athlete or institute/academy squads.

Data collected from your daughter during the study will remain within the confidence of the researchers. Reports will not identify individual participants and only group results will be made available. Group results will be published in scientific journals and presented at scientific conferences. Data will be securely kept within the School of Exercise Science office at the Australian Catholic University, Strathfield, NSW.

Any questions about the above information can be obtained by contacting Dr Elizabeth (Liz) Bradshaw on (03) 9953 3030, email: elizabeth.bradshaw@acu.edu.au, associate professor Geraldine (Jeri) Naughton on (02) 9701 4051, email: g.naughton@mackillop.acu.edu.au or by regular mail at Australian Catholic University, School of Exercise Science, Locked Bag 2002, Strathfield, NSW 2135.

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STUDENT RESEARCHER: MR MARK MORESI

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NAME OF PARENT/GUARDIAN: ....
(block letters)

NAME OF CHILD ....
(block letters)

SIGNATURE ………………………………………………… DATE………/…………/……………

CRICOS registered provider:
00004G, 00112C, 00873F, 00885B

SIGNATURE OF SUPERVISORS:

……………………………………………………………………………………DATE:……/……/………
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(block letters)

SIGNATURE ....DATE................/................/..........

SIGNATURE OF SUPERVISORS:

....DATE:....../....../.........
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....DATE:....../....../.........
Associate Professor GERALDINE NAUGHTON

....DATE:....../....../.........
Dr DAVID GREENE

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Mr MARK MORESI

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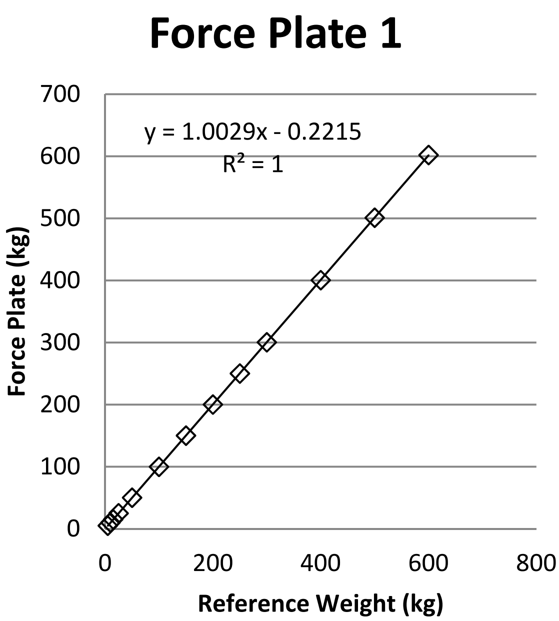
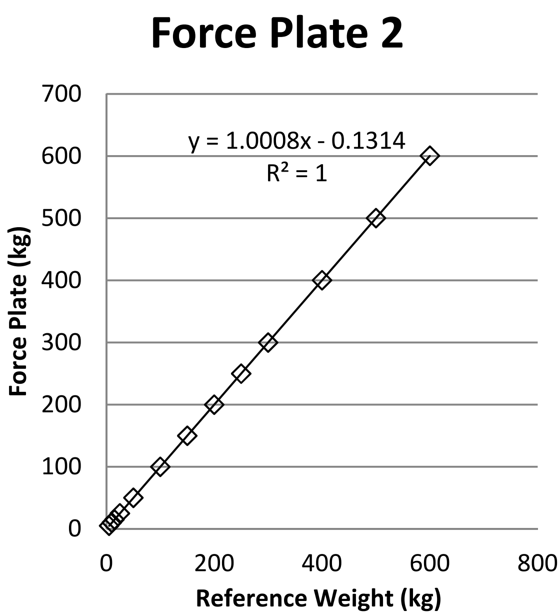
Appendix C: Full Range Force Plate Check Results

Mass (kg)	Force Plate 1			Force Plate 2		
	Mass (kg)	Error	%Error	Mass (kg)	Error	%Error
49.1	48.8	-0.3	0.6	49.0	0.0	0.1
98.1	98.1	0.0	0.0	98.3	0.2	0.2
147.2	147.6	0.4	0.3	147.1	0.0	0.0
245.3	245.1	-0.1	0.0	244.2	-1.1	0.4
490.5	491.4	0.9	0.2	490.3	-0.2	0.0
981.0	979.5	-1.5	0.2	979.8	-1.2	0.1
1471.5	1472.5	1.0	0.1	1470.1	-1.4	0.1
1962.0	1963.7	1.7	0.1	1961.1	-0.9	0.0
2452.5	2453.6	1.1	0.0	2450.9	-1.6	0.1
2943.0	2947.6	4.6	0.2	2942.0	-1.0	0.0
3924.0	3929.3	5.3	0.1	3926.0	2.0	0.1
4905.0	4916.4	11.4	0.2	4906.7	1.7	0.0
5886.0	5907.7	21.7	0.4	5892.0	6.0	0.1





Appendix D: Retrospective Injury Survey

Athlete Medical History / Injury Record Questionnaire

Name: ______________________ Age: ________ School: _____________

General Health

YES NO (Please Tick)

϶ ϶ Have you ever had a heart abnormality or murmur diagnosed by a doctor?

϶ ϶ Do you have asthma, (wheezing), or coughing spells after exercise?

϶ ϶ Do you have a chronic illness or see a physician regularly for any particular problem?
Please List ____

____

϶ ϶ Do you take any medications, or have you taken any medication in the last six months?
Please List ____

____

϶ ϶ Do you have any allergies to medications or any other agents? **Please List** _______

____

϶ ϶ Do you have only one of any paired organ? (eyes, ears, kidneys, testicles) **Please Circle**

϶ ϶ Have you had any surgery or hospitalizations? **Please List** (inc. date)

____

____

____

____

Injury Record

YES NO (Please Tick)

∋ ∋ Have you had any injuries that interfered with your sporting career?

∋ ∋ Have you ever broken a bone, had to wear a cast or had an injury to any joint?

∋ ∋ Do you wear any protective equipment? **Please List: _________________________**

____

∃ NB. IF YOU HAVE ANSWERED YES TO ANY OF THE INJURY RECORD QUESTIONS, PLEASE FILL OUT THE INJURY RECORD FORM ON THE FOLLOWING TWO PAGES.

For each injury:

1) Type of injury ____________________

Approx date ___/___/___

Treatment ____________________

____

Any residual problems? ____________________

How many weeks did you stop training due to the injury? __________

2) Type of injury ____________________

Approx date ___/___/___

Treatment ____________________

____

Any residual problems? ____________________

How many weeks did you stop training due to the injury? __________

3) Type of injury ______________________________

Approx date ___/___/___

Treatment

____

____

Any residual problems? ______________________________

How many weeks did you stop training due to the injury? ____________

4) Type of injury ______________________________

Approx date ___/___/___

Treatment

____

____

Any residual problems? ______________________________

How many weeks did you stop training due to the injury? ____________

Appendix E: Prospective Injury Survey

PERFORMANCE AND INJURY RISK IN ADOLESCENT FEMALE ATHLETES

Injured person's form – parents/guardians of children less than 14 years should complete the form for their child

Name:______________________________ Sex (circle) M / F Date of birth ________________ Home postcode _______________

Sport/Activity in which injury occurred________________ Position played (if appropriate) _____________ Hours of training / competition per week ____

Other sports or physical activity played in the past month (please list activity and hours of training on the table on the back of this page)

When did the injury occur?
□ start of the your sport /training
□ about the middle of your sport/training
□ towards the end of sport/ training

Mechanism of Injury
□ collision with fixed object
□ collision with player / tackle
□ sudden stopping
□ struck by ball / or other sports equipment
□ during a jump
□ during a fall
□ swerving / pivoting
□ overuse
□ other ___________________________

Explain exactly how the injury occurred
____
____
____

Protective Equipment
Was protective equipment or taping used on the injured body part?
□ Yes □ No
If Yes, what type e.g. ankle brace, taping , helmet
____
____

Result of the injury
□ had to stop playing / training
□ after treatment went back to playing

Has this injury occurred before? If yes, was it
□ < 1 month ago □ 1 - 3 months ago
□ 3 - 6 months ago □ 6 - 12 months ago
□ >12 months ago

Have you been diagnosed with any growth-related musculoskeletal condition eg Osgood Schlatter disease (knee), Sever's Disease (heel) Little Leaguer's elbow, Perthes Disease (hip)
(Please List)
____
____

Have you had other injuries that have stopped you training or playing sport?

Please list the injury and time off sport

Injury	Weeks missed

Do you follow a supervised weight training program?
□ Yes □ No
If yes how often and for how long?
____
____

Other medical conditions
Do you suffer from any long term medical conditions eg epilepsy, asthma, diabetes, arthritis, haemophilia (please list)
____
____
____

Have you been diagnosed with attention deficit disorder (ADD or ADHD)?

□ Yes □ No

Do you take any regular medications or supplements?

If YES please list

Name of medication o□ suppleme□t

QUESTION FOR FEMALES ONLY
Have you started your periods? YES/NO
If YES, at what age did they start. (Can you please tell us to the nearest half year eg 12.5 years)
____

PERFORMANCE AND INJURY RISK IN ADOLESCENT FEMALE ATHLETES

Other sports or regular physical activity played in the ***past month***

Sport or Other Regular Activity eg. Dance, Cycling, Riding	Hours per week

PERFORMANCE AND INJURY RISK IN ADOLESCENT FEMALE ATHLETES: *Consultant's Form*

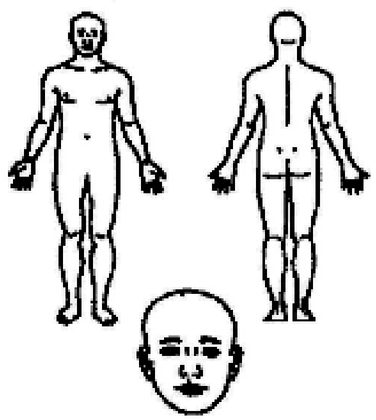
Date of Injury ___/___/___

Time of presentation for treatment ________

Type of activity at time of injury
□ Warm-up
□ Game
□ Supervised training
□ Unsupervised training or play

Reason for presentation
□ new injury
□ exacerbated / aggravated injury
□ recurrent injury
□ chronic condition

Body Region Injured
Tick or circle body part/s injured and name



Body Part/s
____
____
____

Nature of Injury
□ Fracture (including suspected)
□ Stress fracture / reaction
□ Traction apophysitis (eg. Osgood-Schlatter)
□ Osteochondrosis (eg. OCD, Scheuermann's)
□ Ligament sprain / tear
□ Muscle strain / tear
□ Closed head injury
□ Spinal or suspected spinal injury
□ Dislocation / subluxation
□ Laceration / cut
□ Muscle contusion
□ Thermal related (heat stress)
□ Overuse injury to tendon or bone
□ Other ___________________________
□ Not known

Provisional Diagnosis ________________
____

Differential Diagnosis
____
____
____

Imaging (please specify)
____

Advice Given
□ immediate return unrestricted activity
□ able to return with restriction
□ unable to return at present time

Referral
□ no referral
□ specialist referral
(If yes, is surgery required □ yes □ no)
□ physiotherapist or other health professional
□ Emergency Department
□ admission to hospital
□ other (please specify)
____
____

Resuming Activity Assessment
□ minor (return to activity after treatment)
□ mild (1-7 days modified activity)
□ moderate (8-21 days modified activity)
□ severe (> 21 days modified or lost)

Today's Date: ___/____/____

Appendix F: Three-Day Food Diary

MY FOOD RECORD BOOK

This record book belongs to :_______________________

Date of birth : ____________________

MY FOOD RECORD BOOK

Three day food record :

Two week and one weekend days

DAY 1 - Date : ____________________

DAY 2 - Date : ____________________

DAY 3 - Date : ____________________

For further information, please contact Mr Mark Moresi on 9 701 4051 or 0409933696

SECTION 2 : FOOD RECORD

Please write down everything you eat and drink for the same three days that you keep your activity record.

This is not a test. There are no right or wrong answers. Please do not report the foods you think you should be eating or the foods eaten by someone else in your household.

HOW TO FILL IN YOUR RECORD

- Fill in the date and day of the week at the top of the record sheet.
- Use as many pages as you need for each day's record (number each page).
- Start a new page for a new day.

Column 1 – Time

- Every time you have something to eat or drink, write down the time you started.
- Write down « am » for morning and « pm » for afternoon or evening.

Column 2 – What you are measuring

Name and full description of all food and drink.

- Write down everything you eat and drink. This include snacks, water, vitamins and mineral supplements. Eat as you normally would !
- For each food and drink use a new line.
- Measure each food individually, for example, bread and margarine are each separate foods and are recorded on separate lines.
- Always record cooking methods such as boiling, frying, etc.
- Give a detailed description of the food or drink and brand names, for example :
  Arnott's Milk arrowroot Biscuit
  Tip Top White Bread

- Record directly into this book while you still remember, such as while you are making a school lunch.
- Write down a cut of meat, that is lamb loin chop, chicken leg, rump steak etc.
- Write down if the fat on meat or skin on chicken was eaten or not eaten.

Column 3 – Amount eaten

In order to get the best estimate of your nutrient intake we need an accurate estimate of quantities of food and drink consumed.

- Estimate everything as accurately as possible in either **metric cups or spoonfuls** eg teaspoons, tablespoons (level or rounded) such as for breakfast cereal, rice, vegetables or spaghetti, or use a **metric measuring tape or ruler** to give length and width such as for sausage rolls, bananas, etc.

RECIPES

This includes mashed potato, mixed vegetables dishes, gravies and sauces.

- On a separate page record the individual ingredient with quantities. Report the total amount made and the amount of total recipe consumed. See example attached on blue paper.

EATING OUT

- Estimate food eaten as described above.
- Record the main ingredients in the food if recipe is unknown.
- Record where the food came from, such as McDonald's.
- Record weights on wrappers, drink cans and other food containers.

DRINKS

- Measure these in **metric cups or in litre measurements**.
- For cordial, measure the volume of cordial concentrate first then the volume of water added.
- If diluting fruit juice, measure fruit juice and water separately.

SCHOOL LUNCHES

- Estimate these as you prepare them and estimate any left overs in the lunch box.
- Record any extra food eaten at school.
- For canteen lunches, record as described in the Eating Out section.

To assist you in describing amounts of food and drink in household measures, please refer to the following pages.

SALT

(Circle the appropriate answer to each question)

- Do you add salt to food when you cook ?
  Always Sometimes Rarely Never

- Does your child add salt to their food after cooking ?
  Always Sometimes Rarely Never

- Does your child add salt to specific foods (eg chips, tomatoes and eggs)
  Yes No

DATE :_______________________ DAY OF WEEK : _______________________

Column 1 Time	**Column 2** Name, type, brand cooking method	**Column 3** Amount	**Leave blank**

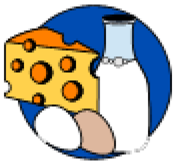
RECIPE SHEET

Name of recipe : ____

Individual Ingredients	Weight or metric measure

Final total cooked weight or amount : ____________________________

SECTION 3 – CALCIUM



HOW TO ANSWER

How often did you eat these foods last week ?

Not last week : **N**
Times a week : **1W, 2W, 3W,** and so on.
Times a day : **1D, 2D, 3D**, and so on.
Please give an answer for every food !

DAIRY FOODS AND EGGS

		How often	Comments
Glass of plain milk (excludes milk on cereal and in hot drinks)	medium glass	______	______
Glass of flavoured milk	medium glass	______	______
Milk shake	regular size	______	______
Thick shake	regular size	______	______
Cheese (including cheddar, colby, edam, brie/camembert)	20 g. (1 slice)	______	______
Reduced fat cheese	20 g. (1 slice)	______	______
Cottage cheese	100 g. (½ carton)	______	______
Cheese Spread	25 g. (1 tbspoon)	______	______
Cheese sauce/cream sauce (eg : on meat/pasta)	3 tbspoon	______	______
Cream	1 tbspoon	______	______
Yoghurt	200 g. (1 carton)	______	______
Ice cream	2 scoops	______	______
Custard	½ cup	______	______
Custard (no added sugar)	½ cup	______	______
Fried egg	1 egg	______	______
Boiled egg/poached	1 egg	______	______
Omelette/scrambled eggs	2 eggs	______	______

DAIRY FOODS AND EGGS I HAVE EATEN THAT HAVE NOT BEEN MENTIONED :

If you had any other dairy foods or eggs in the last 7 days (last week) that we have not mentioned, please write them down below and tell us how often you have them using the same code as before (eg : 1D, 3W).

Name of food	Your usual serve size	How often

Q1. When you drank milk or added it to cereal etc., did you use :

1. Whole milk
2. Shape
3. Reduced fat milk (eg : lite white)
4. Skim milk
5. Farmers best
6. Something else.
   Please describe : ____________________

Please circle one number.

Q2. When you ate yoghurt what type was it ?

1. Plain
2. Plain, low fat
3. Fruit flavoured
4. Fruit flavoured, low fat
5. Diet fruit flavoured (sweetened with Nutrasweet)
6. I did not eat yoghurt.

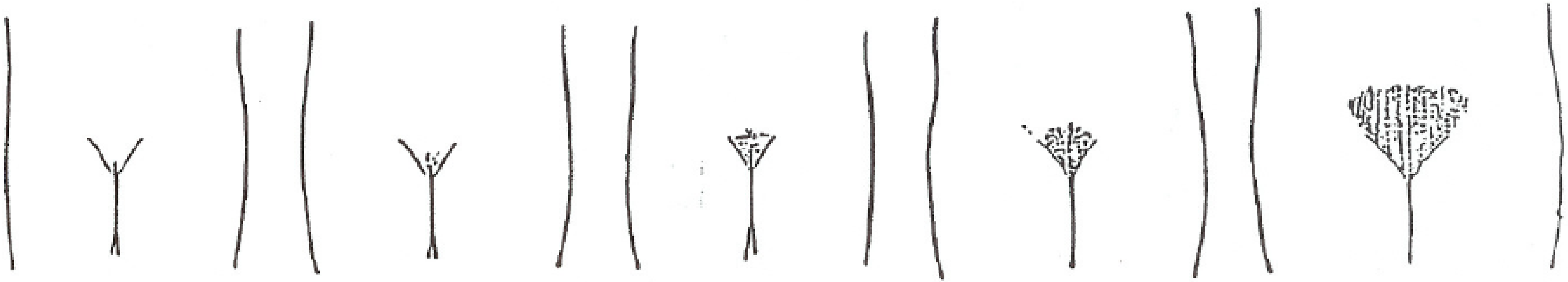
Please circle one number.

When completed, please forward this questionnaire to :

Mr Mark Moresi
School of Exercise Science, Australian Catholic University
Locked Bag 2002,
Strathfield, NSW 2135

Appendix G: Pubertal Assessment Survey

The drawings on this page show <u>different amounts of female pubic hair</u>.
Please look at each of the drawings and read the sentences under the drawings.
Then check the drawing that is **closest** to your stage of hair development.



Picture 1 ___	Picture 2 ___	Picture 3 ___	Picture 4 ___	Picture 5 ___
There is no pubic hair at all.	There is a small amount of long, lightly colored hair. This hair may be straight or a little curly	There is hair that is darker, curlier and thinly spread out to cover a somewhat larger area than in stage 2.	The hair is thicker and more spread out, covering a larger area than in stage 3.	The hair now is widely spread covering a large area, like that of an adult female.

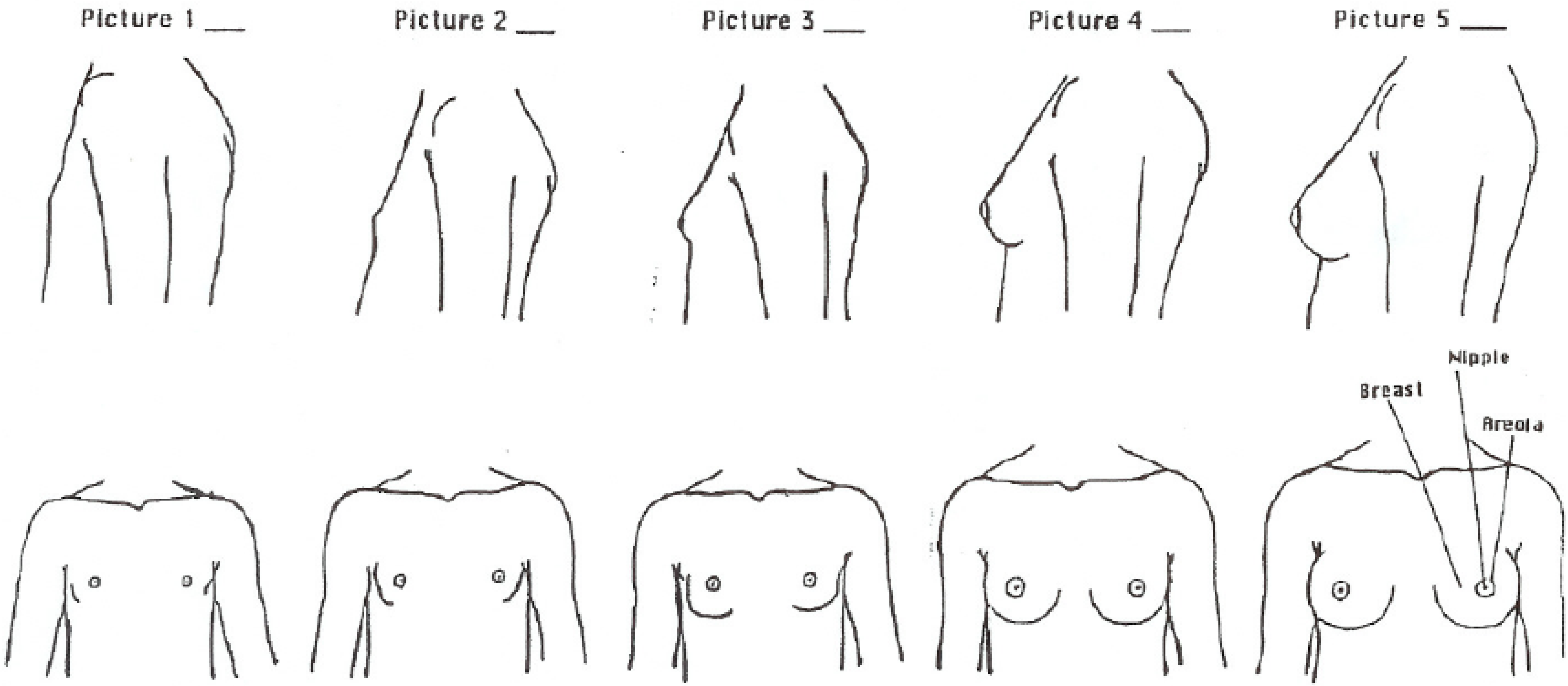
Figure 3.12 Self-assessment of pubic hair development for girls.
Note. The following introduction (written and/or verbal) is given to the child prior to the assessment.

"As you keep growing over the next few years, you will see changes in your body. These changes happen at different ages for different children, and you may already be seeing some changes. Others may have already gone through some changes. Sometimes it is important to know how a person is growing without having a doctor examine them. It can be hard for a person to describe herself or himself in words, so doctors have drawings of stages that all children go through. Five drawings of pubic hair growth are attached for you to look at.

"We want to know how well you can select your stage of growth from the set of drawings. All you need to do is pick the drawing that looks like you do now. Put a check mark above the drawing that is closest to your stage of development, then put the sheet in the envelope and seal it so your answer will be kept private."

Reprinted from Morris and Udry (1980).

The pictures on this page show different stages of how the breasts grow. A girl can go through each of the 5 stages as shown. Please look at each of the pictures. Read the sentences. Put an x on the line above the picture which is closest to your stage of growth.



The nipple is raised a little in this stage. The rest of the breast is still flat.

This is the breast bud stage. In this stage the nipple is raised more than in stage 1. The breast is a small mound. The areola is larger than in stage 1.

The areola and the breast are both larger than in stage 2. The areola does not stick out away from the breast.

The areola and the nipple make up a mound that sticks up above the shape of the breast. (Note: this stage may not happen at all for some girls. Some girls go from stage 3 to stage 5, with no stage 4.)

This is the mature adult stage. The breasts are fully grown. Only the nipple sticks out in this stage. The areola has moved back to the general shape of the breast.

Figure 3.10 Self-assessment of breast development for girls.
Reprinted from Morris and Udry (1980).

Appendix H: Menstrual Status Survey

Name: ______________________________ Date __________

Menstrual Status Questionnaire

We would like you to answer the following questions related to your menstrual cycle as accurately as possible.

1. At what age did you first start menstruating?

   (Can you please tell us to the nearest half year eg 12.5 years) _________

2. How regularly are you currently menstruating

Menstrual cycles in the last year	Yes	No
9	☐	☐
6	☐	☐
3	☐	☐
Less than three	☐	☐
Unable to recall	☐	☐

3. Is the time between cycles predictable?
   (ie: is the time between your periods the same with each cycle?) YES / NO

4. If you menstruate regularly, how many days between the end of your period and the start of the next period? _____________

5. How heavy is the flow of your period:

Flow of the menstrual cycle	Yes	No
Very light	☐	☐
Light	☐	☐
Moderate	☐	☐
Heavy	☐	☐
Very Heavy	☐	☐

6. How long is the flow of your period:

Flow of the menstrual cycle	Yes	No
1 - 2 days	☐	☐
2 - 3 days	☐	☐
3 - 5 days	☐	☐
5 - 7 days	☐	☐
>7 days	☐	☐

7. Do you experience any pain or discomfort during your periods? YES / NO

8. Approximately, at what age did your Mother start menstruating? __________

Appendix I: Gymnast and Track and Field Participant Performance and Event Level Details

Gymnast participant group competition levels at the commencement of baseline testing.

Competition Level	International Level 8	International Level 10	Junior International	Senior International	Total
Baseline	4	10	6	4	24
Longitudinal	2	9	4	2	17

Track and Field participant event groups and performances (mean ± standard deviation) at the commencement of baseline testing.

Event	Sprints#	Middle Distance	Distance	Jumps*	Total
Baseline	15	3	4	9	31
Longitudinal	9	1	4	8	22

Includes sprint hurdles athletes; * Includes Long Jump, Triple Jump and High Jump athletes.

Event	100m	200m	400m	800m	1500m	3000m	100mH (76cm)	400mH	2000mSt	Long Jump	Triple Jump	High Jump
Performance	11.98 ± 0.16	24.50 ± 0.33	56.25 ± 0.93	2:14.50 ± 6.89	4:41.91 ± 15.58	10:19.90 ± 40.31	14.34 ± 0.52	62.94 ± 2.16	7:05.09 ± 5.82	5.61 ± 0.18	11.81 ± 0.05	1.76 ± 0.05

Appendix J: Linear Regression Equations for Adjusted Musculoskeletal Stiffness and Bone Health Markers Used in Injury Prediction

CJb k_{vert}
Gymnast Adjusted Stiffness Measure = -31.661 + 19.556*Jump Frequency (Hz) +0.265*Body Mass (kg) +3.310 'Standard' Gymnast Stiffness = 14.00 kN/m Track & Field Athlete Adjusted Stiffness Measure = -31.661 + 19.556*Jump Frequency (Hz) +0.265*Body Mass (kg) +3.751 'Standard' Track & Field Athlete Stiffness = 14.44 kN/m 'Standard' Athlete: Jump Frequency = 1.4010 Hz, Body Mass = 56.4275 kg

CJs k_{vert}
Gymnast Adjusted Stiffness Measure = -41.322 + 21.566*Jump Frequency (Hz) +0.319*Body Mass (kg) + 9.197 'Standard' Track & Field Athlete Stiffness = 24.16 kN/m Track & Field Athlete Adjusted Stiffness Measure = -41.322 + 21.566*Jump Frequency (Hz) +0.319*Body Mass (kg) + 10.548 'Standard' Gymnast Stiffness = 25.52 kN/m 'Standard' Athlete: Jump Frequency = 1.7757 Hz, Body Mass = 56.4275 kg

CJb30Early k_{conc}
Gymnast Adjusted Stiffness Measure = -30.345 + 17.976*Jump Frequency (Hz) +0.250*Body Mass (kg) + 2.466 'Standard' Gymnast Stiffness = 13.76 kN/m Track & Field Athlete Adjusted Stiffness Measure = -30.345 + 17.976*Jump Frequency (Hz) +0.250*Body Mass (kg) + 1.886 'Standard' Gymnast Stiffness = 11.87 kN/m 'Standard' Athlete: Jump Frequency = 1.5684 Hz, Body Mass = 56.0099 kg

CJb30Late k_{conc}
Gymnast Adjusted Stiffness Measure = -29.980 + 16.240*Jump Frequency (Hz) +0.274*Body Mass (kg) + 3.561 'Standard' Gymnast Stiffness = 16.03 kN/m Track & Field Athlete Adjusted Stiffness Measure = -29.980 + 16.240*Jump Frequency (Hz) +0.274*Body Mass (kg) + 3.522 'Standard' Gymnast Stiffness = 15.99 kN/m 'Standard' Athlete: Jump Frequency = 1.6678 Hz, Body Mass = 56.0099 kg

Tibia 4% SSI
Gymnast
Adjusted Stiffness Measure = 287.619 + 3.679*Tibia Length (mm) + 644.716
‘Standard’ Gymnast SSI = 2314.18 mm^3
Track & Field Athlete
Adjusted Stiffness Measure = 287.619 + 3.679*Tibia Length (mm) + 523.532
‘Standard’ Gymnast SSI = 2193.00 mm^3
‘Standard’ Athlete Tibia Length = 367.0796 mm

*Note.*To calculate an athlete ‘at risk’ based on the present thesis model, insert the athlete details into the appropriate equation above following testing (assuming the same protocols and jump surface for the jump tasks are used to standardize the results). This will give you an ‘expected’ score based on the regression output. Calculate the difference between the ‘expected’ score and the observed score for that athlete which will give you a ‘residual’. This ‘residual’ value is then added or subtracted from the ‘standard’ athlete value which can be calculated by inserting the ‘standard’ athlete details into the appropriate equation for the required sporting group. The value for that particular athlete can then be compared to the cutoff values shown in Table 8.4 to identify if your athlete may be at increased injury risk basedon the findings of this thesis.

Appendix K: Receiver Operating Characteristic (ROC) Curve Summary Results for all Musculoskeletal Stiffness Measures

Stiffness Measure	General Lower Limb Injury		Lower Limb Acute Injury		Lower Limb Overuse Injury		Lower Limb Fracture	
	Area	p-value	Area	p-value	Area	p-value	Area	p-value
CJb k_{vert}	0.662	0.131	0.500	1.000	0.666	0.079	0.565	0.578
CJb k_{Fi}	0.617	0.274	0.503	0.976	0.615	0.223	0.512	0.917
CJb k_{ave}	0.621	0.260	0.506	0.952	0.628	0.174	0.540	0.728
CJb k_{conc}	0.617	0.274	0.524	0.812	0.634	0.157	0.569	0.554
CJs k_{vert}	0.586	0.421	0.624*	0.211	0.762	0.006	0.601	0.385
CJs k_{Fi}	0.579	0.459	0.607*	0.283	0.749	0.008	0.613	0.330
CJs k_{ave}	0.600	0.351	0.598*	0.326	0.749	0.008	0.637	0.237
CJs k_{conc}	0.572	0.499	0.550*	0.613	0.684	0.051	0.649	0.198
CJb30Early k_{vert}	0.448	0.629	0.435	0.512	0.583	0.380	0.617	0.313
CJb30Early k_{Fi}	0.448	0.629	0.447	0.592	0.570	0.462	0.605	0.366
CJb30Early k_{ave}	0.462	0.723	0.456	0.655	0.583	0.380	0.641	0.223
CJb30Early k_{conc}	0.559	0.585	0.479	0.835	0.663	0.084	0.710	0.071
CJb30Late k_{vert}	0.476	0.822	0.402	0.326	0.634	0.157	0.625	0.281
CJb30Late k_{Fi}	0.445	0.607	0.429	0.475	0.570	0.462	0.601	0.385
CJb30Late k_{ave}	0.448	0.629	0.453	0.634	0.551	0.590	0.613	0.330
CJb30Late k_{conc}	0.476	0.822	0.467	0.743	0.561	0.515	0.625	0.281
ΔCJb30 k_{vert}	0.534*	0.098	0.541	0.677	0.537*	0.692	0.597*	0.404
ΔCJb30 k_{Fi}	0.559*	0.101	0.530	0.766	0.553*	0.571	0.573*	0.531
ΔCJb30 k_{ave}	0.590*	0.103	0.527	0.789	0.588*	0.350	0.625*	0.281
ΔCJb30 k_{conc}	0.638*	0.198	0.438	0.532	0.636*	0.149	0.730*	0.089

Note. * Variable reversed in curve analysis. i.e. smaller values indicate a potential ‘positive’ link with injury.

Appendix L: Associated Publications & Conference Presentations

Peer-Review Journal Manuscripts

Moresi, M.P., Bradshaw, E.J., Greene, D.A. & Naughton, G.A. (2011). The assessment of adolescent females using standing and reactive long jumps. *Sports Biomechanics*, in press.

Peer-Review Conference Proceedings

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