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The Effects of an 8-week Integrated Neuromuscular Training Programme on Pre-Pubescent Female Gymnasts' ACL Injury Risk

(Dissertation submitted under the discipline of Sports Conditioning, Rehabilitation and Massage)

Sylvia Moeskops

20000498

THE EFFECTS OF AN 8-WEEK INTEGRATED NEUROMUSCULAR TRAINING PROGRAMME ON PRE-PUBESCENT FEMALE GYMNASTS' ACL INJURY RISK

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ABSTRACT

Previous research has demonstrated the effectiveness of integrated neuromuscular training (INT) programmes on ACL injury risk measures in young females, with a games-specific background. The effects of an INT intervention on pre-pubescent gymnasts' core strength (flexor and extensor maximum holds), movement competency (Functional Movement Screening), leg stiffness (sub-maximal hopping) and Time to Stabilisation (TTS) remain unclear. Thirty-six pre-pubescent female gymnasts participated and were divided equally into a training or control group, according to the days they trained already on. The training group followed an 8-week INT programme, twice a week, whilst the control continued with their usual training schedule. Core strength, movement competency, leg stiffness and time to stabilisation (TTS) measures were collected pre and post the intervention. The training group made significant improvements ($P< 0.05$) in core strength measures, not seen in the control. The training group maintained leg stiffness whilst the control's significantly decreased ($P< 0.05$). Movement competency improved in the training group (median values of functional movement screening increased from 1 to 2), but remained the same for the control. There were significant ($P< 0.05$) decreases in TTS for the non-dominant leg of both groups, but only a significant ($P< 0.05$) reduction in TTS for the control group's dominant leg. The study provides evidence to suggest that an integrated neuromuscular training programme which targets several components (core strength, leg stiffness, movement competency and TTS), can produce positive training outcomes which could reduce the risk of ACL injury in young gymnasts.

CHAPTER 1

INTRODUCTION

Epidemiological research has shown that females who participate in sports involving landing, cutting and pivoting, are four to six times more likely to injure their anterior cruciate ligament (ACL) than their male counterparts (Arendt & Dick, 1995). The ACL is one of the major stabilising intracapsular ligaments in the knee joint, and it prevents excessive anterior translation of the tibia on the femur (Silvers & Mandelbaum, 2007). Injuries to the ACL account for approximately 50 percent of all knee injuries (Risberg, Lewek & Snyder-Mackler 2004). The severity of this injury is grade dependent, where more serious cases require surgical repair followed by extensive rehabilitation (Risberg et al., 2004). This injury can be career ending and have long term implications (Mansson, Kartus & Sernert 2011), such as the early development of osteoarthritis (Fleming, 2003) and reduced physical activity long term (Mansson et al., 2011).

The gender disparity of non-contact ACL injuries has lead researchers to question the underlying mechanism that increases females' injury risk (Ford et al., 2010: Hewett et al., 2006a: Myer et al., 2009). Anatomical, hormonal, neuromuscular, and biomechanical theories have been proposed by researchers (Ford, Shaprio et al. 2010: Hewett et al. 2006a: Silvers & Mandelbaum, 2007), which suggest the mechanism is most likely to be multifactorial in nature (Hewett et al., 2006a). Anatomical theories posit that females' are more susceptible to ACL injuries due to their greater joint laxity and hamstring flexibility (Hewett et al., 2006a). This in turn increases the possibility of hyperextension and knee valgus rotation (Hewett et al., 2006a), as well as reducing co-contraction between the quadriceps and hamstrings (Quatman-Yates et al., 2013). Fluctuations in female hormones during normal menstrual cycles may alter the tensile properties of the ACL (Silvers & Mandelbaum, 2007), consequently reducing the ligaments ability to tolerate load (Wild et al., 2012). Males demonstrate significant increases in muscular power, strength, and coordination during adolescence (Myer et al., 2005). However, this neuromuscular spurt appears to be absent in most females (Myer et al., 2005). Females have shown neuromuscular deficits not seen in males during sporting activities, such as higher knee abduction moments when landing (Myer et al., 2010), reduced leg stiffness (Lloyd et al., under review) and decreased coactivation of the quadriceps and hamstrings (Hewett et al., 2006a). Furthermore, biomechanical analysis has demonstrated that females have poorer proximal control than males (greater hip adduction and internal rotation) and rely more on transverse and frontal planes during landing as opposed to sagittal (Pollard et al., 2007).

As there is no conclusive evidence that anatomic and hormonal risk factors are directly correlated with ACL injury risk in females (Myer et al., 2013), researchers have focused on implementing preventative programmes to address neuromuscular and biomechanical deficits (Paterno et al., 2004: Ford, Sharprio et al., 2010: Hewett & Myer., 2011: Myer et al., 2013). Importantly, integrated neuromuscular training (INT) interventions are effective in reducing ACL injury risk in females (Myer et al., 2005: Paterno et al., 2004: Myer et al., 2013) through enhancing joint stability, improving joint position sense and developing protective joint reflexes (Padua & Marshall, 2006). A recent meta-analysis demonstrated that these positive training outcomes are more effective in reducing ACL injury risk when implemented with pre or early adolescent-aged female athletes (Myer et al., 2013). Such programmes may induce a neuromuscular spurt (not normally seen in females) (Myer et al., 2005), to address the onset of neuromuscular deficits and abnormal biomechanics which develop during the pubertal growth spurt (Ford, Myer & Hewett, 2010). Furthermore, INT programmes that include: plyometrics, dynamic stabilization, strength, and feedback-driven technique training, were found to be the most effective means of training with youths (Myer et al., 2013). Although there is a growing body of research in this area, all of the studies included in the meta-analysis used female participants involved in games specific sports (soccer, handball, volleyball and so forth). Therefore, the effects of INT programmes on ACL injury risk in youth athletes from non-games sports remains unclear.

Female artistic gymnastics is an early specialisation sport that involves higher training loads (volume and intensity) than other sports for children of similar ages (Burt et al., 2010). Injuries to the ankle and knee are the most common sites of injury in gymnastics (Kirialanis et al., 2002). Higher injury rates occur on the floor apparatus for both males and females; however females are injured more often during landings (Kirialanis et al., 2002). Additionally, epidemiological research has reported that women's gymnastics has the highest rate of ACL injuries per 1000 across 15 sports (Hootman et al., 2007). The frequent exposure to large forces during landings and dismounts (Gittoes & Irwin, 2012) may predispose young female gymnasts to a heightened risk of non-contact ACL injury. Furthermore, evidence suggests that impact forces and injury risk increases for gymnasts as they progress through the competitive levels, performing more complex skills (Caine, Nassar & Maffuli 2005). With ACL injury incidences increasing in females following puberty (Ford, Myer et al., 2010), and gymnasts performing more advanced skills with age, the need for effective injury prevention programmes is clear. Implementing INT programmes that could reduce the risk of such a traumatic injury in young gymnasts is essential, especially when considering that ACL ruptures in these athletes was found to be a reason for early retirement (Sands, 2000).

To date, the effects of an INT programme on young gymnasts' injury risk, has not yet been examined. The purpose of the current study is therefore to implement and evaluate an 8-week INT programme with pre-pubescent gymnasts, to assess whether or not their overall ACL injury risk profile lessens. The hypothesis was that the ACL injury risk in the gymnasts participating in the 8-week training intervention would be reduced, whilst the control groups would remain unchanged.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

Previous research has shown that 70 percent of all ACL injuries are non-contact in origin (Silvers & Mandelbaum, 2007). Landing, decelerating and pivoting during sporting activities are recognised as common movement patterns during which non-contact ACL injury can occur (Kirkendall & Garrett, 2000: Silvers & Mandelbaum, 2007). Current research suggests that female athletes are more susceptible to ACL tears than males, with incidence rates between 2.4 and 9.7 times higher (Agel et al., 2005). A previous meta-analysis revealed that ACL injury rates in female basketball players and footballers were approximately three times that of males (Arendt & Dick, 1995). The gender disparity in ACL injury rates appears to be multifactorial in nature, relating to differences in anatomical, hormonal, neuromuscular and biomechanical factors (Ford, Sharprio et al., 2010: Hewett et al., 2006a: Myer et al., 2009). Examples of intrinsic risk factors include: joint laxity, dynamic valgus knee, hip control and strength, joint stiffness and co-contraction ratios (Hewett et al., 2006a: Myer et al., 2009). The differences in these intrinsic risk factors are thought to develop during the adolescent growth spurt in female athletes (Ford, Myer et al., 2010). Whilst males demonstrate significant increases in muscular power, strength, and coordination during adolescence, females do not exhibit similar traits (Myer et al., 2005). Furthermore, in certain instances, neuromuscular ability decreases in females (Hewett et al., 2006a). Immediately after this period of rapid growth, females continue to have higher ACL injury rates in comparison to males, inherent in their absence of naturally occurring neuromuscular adaptation (Hewett et al., 2004: Myer et al., 2009).

Artistic gymnastics is an early age specialisation sport involving intensive training and high level competition, at a time when structures in the body are still developing. Elite youth gymnasts (children and adolescents) may eventually be subjected to training volumes of 40 hours per week, 5 to 6 hours per day, for up to 12 months per year (Sands, 2000). Owing to the excessive loadings experienced by this population from such intense programmes, and those from other elite youth sports, researchers have highlighted the need for appropriate injury prevention strategies (Hewett et al., 2006b: Faigenbaum & Myer, 2010: Faigenbaum et al., 2011). The content of injury prevention strategies for young athletes should be multidimensional in nature, encompassing a variety of training modalities inclusive of dynamic stabilization, fundamental movement skill development, speed and agility, and resistance training (Myer et al., 2011). Resistance training for youths is now recognized globally as a safe and effective exercise modality which can reduce injury risk and enhance performance, when appropriately designed, implemented and supervised by suitably qualified professionals (Lloyd et al., 2014). A wealth of research now exists demonstrating that age-appropriate integrated neuromuscular programmes can reduce ACL injury risk in young female athletes (Paterno et al., 2004: Myer et al., 2008: Myer et al. 2013), and that the effectiveness of such programmes is age-related (Myer et al., 2013).

2.2 Mechanisms of ACL Injuries in Female Athletes

2.2.1 Anatomical Mechanisms

Females generally have greater joint laxity and hamstring flexibility than males (Boden et al., 2000), and these structural differences have been identified as risk factors for ACL injury (Hewett et al., 2006a). Joint laxity may predispose female athletes to ACL tears through increased risk of hyperextension and valgus rotation at the knee joint (Hewett et al., 2006). Hamstring flexibility tends to decrease with maturation in boys, but increases in girls following puberty (Hewett et al., 2006a). Greater hamstring flexibility may delay muscle activation early in the stance phase, which results in the reduction of co-contraction between the quadriceps and hamstrings (Ford, 1997: Quatman et al., 2013), and decreased dynamic knee stability. These structural risk factors for ACL injury may be particularly relevant to gymnasts, due to the sport's greater demands for hyper-flexibility and extreme ranges of motion (Douda et al., 2008).

Other research has focused on what affects athletes ACL injury risk during different stages of maturation (Myer et al., 2009: Wild et al., 2012). In a study on the effects of maturation in youth soccer players, no gender differences in knee injury risk of children aged five to 12 that were prepubescent were found (Buehler-Yund et al., 1999). However, the authors estimated greater risk in girls from the age of 12 due to increases in body mass index (Buehler-Yund et al., 1999), which often occurs in the absence of a concomitant increase in muscular strength (Myer et al., 2009: Quatman et al., 2013). A recent longitudinal report assessed the effects of maturation on ACL risk factors in a female athlete (Myer et al., 2009). The authors noted that as the athlete matured, centre of mass height increased, placing greater demands on the individual's core and trunk control (Myer et al., 2009). However, concomitant increases in relative hip abduction and hamstring strength to meet these demands were not present (Myer et al., 2009). The absence of such adaptations may have influenced the knee abduction loads, predisposing the individual to an increased risk of ACL injury (Myer et al., 2009). This highlights the importance of females engaging in strength training (inclusive of core strength exercises) as part of an integrative neuromuscular ACL injury prevention programme. Furthermore, it has recently been demonstrated that hamstring and quadriceps strength deficits and imbalances emerge in females during pubertal maturation (Quatman et al., 2013). The initiation of integrative neuromuscular ACL injury prevention programmes should occur no later than early adolescence, in order to minimise the risk of injury caused as a result of puberty-induced alterations in biomechanics (Myer et al., 2013: Quatman et al., 2013). Whilst a wealth of research now exists investigating the effectiveness of injury prevention programmes on adolescent female athletes (Myer et al., 2013), there is a dearth of research examining the effects of an INT injury prevention programme on ACL injury risk factors in prepubescent athletes.

2.2.2 Hormonal Mechanisms

Concentrations of hormones including oestrogen, progesterone and relaxin, fluctuate during different phases of the menstrual cycle (Silvers & Mandelbaum, 2007). The ACL's integrity is affected by fluctuations in these hormones, which consequently reduce the rate of collagen synthesis by up to 40 percent (Silvers & Mandelbaum, 2007). As collagen provides mechanical strength to the ACL, this structural change may reduce the ligaments' ability to withstand load (Wild et al., 2012). Altered tensile properties of ligaments during females' normal menstrual cycle may affect the incidence of ACL injury directly (Silvers & Mandelbaum, 2007).

Moreover, as reported in a recent review, females may be at greater risk of ACL injury during the onset of puberty, due to a considerable influx of oestrogen (Wild et al., 2012). Oestrogen can influence the strength and function of tendons and ligaments, which may affect the normal neuromuscular control of the knee joint (Hewett et al., 2006). Thus, these changes during puberty may impact upon knee joint laxity and reduce stability, increasing the risk of ACL injury (Wild et al., 2012). Further research is needed to assess how the pubertal oestrogen influx affects knee laxity, due to discrepancies in the way in which the studies tracked the participants' pubertal development (Wild et al., 2012).

2.2.3 Neuromuscular Mechanisms

Coactivation of the hamstrings and quadriceps protects the knee ligaments, and any strength or activation deficits in the hamstrings will directly limit the ability of the muscle to co-contract (Hewett et al., 2006a). Research has shown that females have decreased hamstring-to-quadriceps peak torque ratio (Quatman et al., 2013) and increased knee valgus rotation compared with males, thus increasing their risk of ACL injury (Hewett et al., 2006a). Therefore, developing sufficient hamstring strength to aid the ACL in young female gymnasts may be crucial in reducing injury risk during dynamic movements, such as landing (Wild et al., 2012). Furthermore, high knee abduction moments (KAM) occur in females during landing and derive from: increased knee valgus, knee flexion range of motion, body mass, tibia length, and quadriceps-to-hamstrings ratio (Myer et al., 2010). Early screening for these variables should be prioritised (Myer et al., 2010), as early training interventions are most effective in high-risk females (Myer et al., 2013).

Another neuromuscular mechanism that provides protection to the knee joint through dynamic stability is leg stiffness (Alentorn-Geli et al., 2009). During stretch shortening cycle (SSC) activities, leg stiffness represents the ratio between peak ground reaction forces and peak centre of mass displacement at ground contact (McMahon & Cheng, 1990). Sex related differences in lower limb stiffness exist between males and females following a pubertal growth spurt (Ford, Sharprio et al., 2010), with females demonstrating reduced stiffness at the hip, knee and ankle (Ford, Sharprio et al., 2010). Athletes with lower measures of leg stiffness will be less efficient at tolerating loads upon contact with the ground (Ford, Sharprio et al., 2010), and consequently their ability to regulate forces when landing is reduced, thus increasing their potential risk for ACL injury.

Recently, Lloyd et al. (under review), examined the effects of a soccer specific fatigue protocol on leg stiffness in female youth players of different ages and maturational status. The results demonstrated that the fatigue protocol decreased leg stiffness, causing an induced inhibitory response in the pre-pubertal athletes (Lloyd et al., under review). The authors proposed that neuromuscular changes in the activation of the musculo-tendon unit occurred due to the presence of fatigue (Lloyd et al., under review). Consequently, reduced leg stiffness in pre-pubertal athletes may increase their risk of ACL injury, highlighting the need for appropriate intervention programmes in child athletes (Lloyd et al., under review).

2.2.4 Biomechanical Mechanisms

The kinetic and kinematic gender differences underlying ACL injuries have been researched and reviewed extensively (Decker et al., 2003: Hewett et al., 2004: Hewett et al., 2006a: Wild et al., 2012). There appears to be no evidence to suggest ACL injury risk factors such as dynamic knee stability and increased valgus moments differ in prepubescent boys and girls (Hewett et al., 2004). However, immediately after an adolescent growth spurt these measures have been shown to increase in females (Hewett et al., 2004: Hewett et al., 2006a). Ford et al. (2010) demonstrated pubertal females' knee abduction angles significantly increased during rapid adolescent growth, whereas males' did not. Females appear to have poorer proximal control than males, with reported greater hip adduction and internal rotation when landing (Pollard et al., 2007). Furthermore, females' landing strategies appear to differ from males as they tend to rely on transverse and frontal planes rather than sagittal (Pollard et al., 2007). Sex related differences in lower limb biomechanics occur when a deficiency in neuromuscular adaptation leads to abnormal joint mechanics, which results in greater risk of ACL injury in young females (Myer et al., 2013). Importantly, in a recent meta-analysis, Myer et al. (2013) found that integrated neuromuscular programmes implemented with athletes to reduce ACL injury risk, were most effective when implemented earlier.

2.3 Methods of Assessing ACL Injury Risk

2.3.1 Motion Analysis

As the mechanism of ACL injury appears to be multifactorial in nature (Ford, Sharprio et al. 2010: Hewett et al. 2006: Myer et al. 2009), methods of assessing ACL injury risk have varied considerably. Myer et al. (2005) used three-dimensional motion analysis to examine knee joint values (flexion and extension angles, valgus and varus torques) during the landing phase of a vertical drop jump. Subjects at greater risk of ACL injury display high varus and valgus knee torques, as well as reduced knee range of motion (Myer et al., 2005). *Figure 1* shows the position of the tibia and femur for an individual with normal (a), valgus (b) and varus (c) knee biomechanics. The vertical drop jump has been frequently used in studies to assess ACL injury risk (Myer et al., 2005: Kernozek et al., 2008: Ford, Sharprio et al., 2010), as it is proven to have high within session and between-session reliability (Ford, Sharprio et al., 2003). However, Myer et al. (2010) noted that such laboratory based methods are not time and cost effective when screening individual athletes on a large scale. High knee abduction moments (KAM) during landing are often reported at the time of ACL injury in females, which derive from: increased knee valgus, knee flexion range of motion, body mass, tibia length, and quadriceps-to-hamstrings ratio (Myer et al., 2010). Therefore, Myer et al. (2010) developed and validated a clinic-based assessment tool (nonogram) using these variables, to predict females with high KAM landing mechanics on a wider scale. An individual's probability of demonstrating high KAM is calculated from the total points scored, from the five ACL predictor variables (Myer et al., 2010). Once identified, appropriate training interventions can be implemented with high risk athletes to reduce ACL injury potential (Myer et al., 2013).

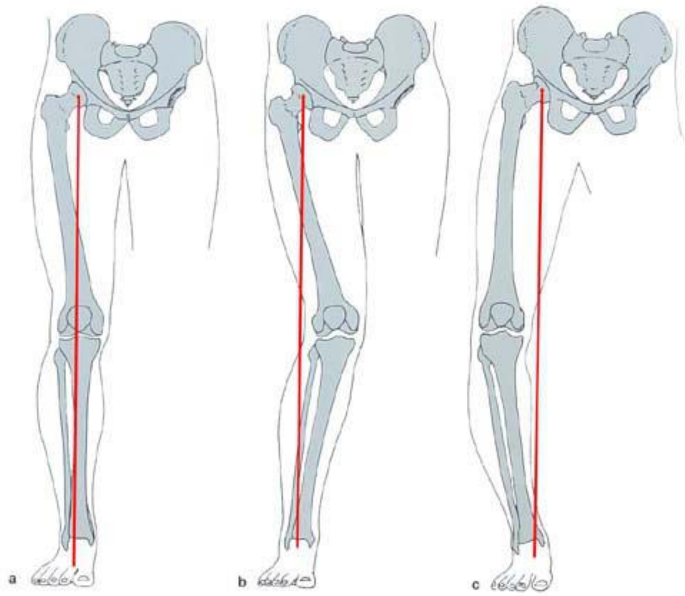

Figure 1. The position of the tibia and femur for an individual with normal (a), valgus (b) and varus (c) knee biomechanics (Orthopedie Hernetals (Updated) Online)

2.3.2. Field-based Stiffness Assessment

Evaluating athletes' leg stiffness is an important predictor for ACL injury. Reduced stiffness will typically mean that individuals are less able to tolerate forces upon contact with the ground (Lloyd et al., under review). Dalleau et al. (2004) demonstrated the validity of a field-based method to calculate leg stiffness using ground contact times, flight times, and body mass, from a contact mat. However, Lloyd et al. (2009) later highlighted the absence of reliability and validity of such methods for leg stiffness in youths. Lloyd et al. (2009) therefore compared force plate and contact mat leg stiffness data, and found sub-maximal hopping to be a valid field-based tool within paediatric populations.

2.3.3 Movement Competency Screening

The Functional Movement Screen is a field-based method used to assess an athlete's motor skill competency during simple movement patterns (Cook et al., 2006a: Cook et al., 2006b). It enables coaches to identify compensatory or inefficient movements, which may lead to poor biomechanics and as a result, predispose athletes to injury (Cook et al., 2006a: Cook et al., 2006b). Therefore, identifying abnormal mechanics in pre-pubescent athletes that are associated with ACL injury (knee valgus), may allow coaches to begin preventative programmes earlier and reduce injury risk.

2.3.4 Time to Stabilisation

Time to stabilisation (TTS) is a method of assessing ACL injury risk which quantifies an athlete's neuromuscular control and postural stability during the landing phase of a jump (Wikstrom et al., 2004). TTS employs a force plate to calculate the time taken for an athlete's vertical ground-reaction forces to stabilise after the landing from a jump, within five percent of their body weight (Flanagan et al., 2008). Although TTS did not prove to be a reliable protocol (Flanagan et al., 2008), Flanagan et al. (2008) noted that with appropriate habituation periods, TTS could be a valuable tool for coaches to establish any lower limb instability.

2.4 Effectiveness of ACL Prevention Training Interventions in Young Athletes

2.4.1 Effectiveness of Neuromuscular Training Interventions on Youths' ACL Injury Risk

The clear gender disparity in ACL injuries has led researchers to question the most effective time and type of intervention strategy with youth populations, particularly with females (Myer et al., 2005: Ford, Sharprio et al., 2010: Myer et al., 2013). A recent position statement highlighted the need for young females to regularly participate in multifaceted resistance programmes to reduce the risk of ACL injury (Lloyd et al., 2014). Neuromuscular training interventions are thought reduce injury risk through enhancing joint stability, improving joint position sense and developing protective joint reflexes (Padua & Marshall, 2006). The effects of such programmes on young females have been explored to address the current ACL epidemiology (Myer et al., 2005: Paterno et al., 2004: Myer et al., 2013). Paterno et al. (2004) reported significant improvements in young females' (aged 13-17) single leg postural stability following a 6-week neuromuscular programme. Although the findings are demonstratively positive, the study did not include a control group, which may potentially limit its value. Later, Myer et al. (2005) noted that female baseline levels of strength and power are commonly lower than males. Following a multi-component neuromuscular intervention, the adolescent females' demonstrated significant improvements in the lower extremity biomechanics (decreased knee valgus (28%) and varus (38%) torques) when compared with controls. However, the study concluded by speculating that if used with children, similar programmes could achieve greater benefits both in performance and injury prevention. Implementing injury prevention programmes in child athletes may improve deficits that later accelerate during maturation and lead to increased musculoskeletal risk (Ladenhauf et al., 2013: Quatman-Yates et al., 2013: Myer et al., 2013).

Other neuromuscular training programmes used to address ACL injury risk in females, have focused on strengthening trunk and hip stabilisers, to address abnormal biomechanics that occur during adolescence (Myer et al., 2008). Myer et al. (2008) emphasise the importance of developing core neuromuscular control in females to pre-activate trunk and hip stabilisers during sporting activities, which could potentially increase knee abduction loads and ACL injury risk. Pilot studies with female athletes found neuromuscular training that targeted the trunk increased hip abduction strength, resulting in improved control of the lower extremity and reduce knee abduction loads during dynamic tasks (Myer et al., 2008). Though the study proved to be successful, Myer et al.

(2008) suggested future research is needed to determine if such programmes can induce a neuromuscular spurt in pre-pubescent females. Later, Hewett and Myer (2011) concluded that there is strong evidence to suggest effective core based interventions can reduce ACL injury incidences in females. Decreased neuromuscular control of the trunk during landing activities may increase knee abduction joint loads through lateral trunk motion and reactive hip adduction torques, thus increasing ACL injury risk (Hewett & Myer, 2011).

2.4.2 Additional Benefits of Neuromuscular Programmes with Youths

Though the positive training effects of dynamic neuromuscular interventions in reducing lower limb injury risk in females have been demonstrated (Myer et al., 2008), some authors have questioned whether or not such programmes can also improve performance measures (Myer et al., 2005). If such programmes were available, athletes would possibly be more motivated to participate in neuromuscular training (Myer et al., 2005). Myer et al. (2005) therefore investigated the effects of a 6-week INT programme and found it had a synergistic effect, improving measures of performance (predicted 1 repetition maximum squat, bench press, single-leg hop distance, vertical jump height and speed) and lower extremity movement biomechanics (decreased in valgus and varus values) in adolescent females (Myer et al., 2005).

Faigenbaum et al. (2011) recently studied the effects of an INT programme on 40 elementary school children. The results showed significant improvements in both health and skill related fitness components in the experimental group, which the traditional physical education lessons did not. Importance was placed on the inclusion of a strength component in INT programmes for children, as it underpins the ability to perform fundamental movement skills (FMS) (Faigenbaum et al., 2011). Programmes that improve FMS in children can consequently have a positive influence on physical ability during adolescence (Barnett et al., 2009). Myer et al. (2013) accentuated that children's experience of physical activity should begin with preparatory fitness conditioning, before competitive sport is introduced, to reduce risk of injury occurring later during maturation. Though the research was clearly valuable, it was based on primary school children as opposed to young athletes. A meta-analysis reported that young non-athletes gained greater adaptations in motor performance following training programmes than athletes, due to higher learning effects (Behringer et al., 2010). Therefore, future research is needed to examine the multidimensional effects of INT programmes with experienced young athletes.

2.4.3 Optimal Time to Implement Neuromuscular Training Interventions

Children develop biologically at different rates, therefore chronological age is not a valid or reliable indication of maturation, or crucially when ACL injury risk may increase (Wild et al., 2012). Time from Peak Height Velocity (PHV) is a more accurate predictor of when the onset of puberty occurs (Tanner et al., 1976), which refers to the peak growth in height during an adolescent growth spurt (Tanner et al., 1976). Greater incidences of non-contact ACL injuries occur in females at PHV (Wild et al., 2012), Therefore, implementing injury preventative programmes with youths at a certain time may be essential in reducing ACL injury rates, especially when such injuries are occurring more frequently in children (Ladenhauf et al., 2004).

Timing neuromuscular training with growth may encourage a neuromuscular spurt (not normally seen in girls) that could potentially enhance performance and reduce injury risk in young females (Lloyd et al., 2014). A meta-analysis conducted by Myer et al. (2013) investigated the optimal time to implement such training programmes with females to reduce the risk of ACL injuries. The findings indicated that this was the period prior to, or in early adolescence, before the risk of injury is increased due to altered mechanics (Myer et al., 2013). The analysis revealed the importance of early intervention with 72 percent risk reduction in females under the age of 18, as opposed to just 16 percent in over 18 year olds. Quatman-Yates et al. (2013) suggest that appropriate programmes with pre-pubescent females, may address the strength imbalances that occur in the quadriceps and hamstrings during puberty. This could be particularly relevant for athletes involved in early specialisation sports, as training volume and intensity have been identified as significant factors for increased injury risk (Steinberg et al., 2014). Furthermore, Ladenhauf et al. (2013) stated that appropriate neuromuscular training that emphasises correct landing techniques and coordinated movement patterns, can prevent ACL injury in competitive youth athletes. In addition, pre-pubertal female athletes may be more susceptible to ACL injuries once fatigued, as a result of reduced leg stiffness (Lloyd et al., in press).

The optimal time to begin implementing injury prevention programmes, may therefore be with pre-pubescent athletes, before the onset of neuromuscular deficits and biomechanical abnormalities occur (Lloyd et al., 2014). This highlights the need for coaches to identify lower limb ACL risk factors (such as valgus rotation) in child athletes (Ladenhauf et al., 2013: Lloyd et al., 2014). Injury prevention programmes that include: plyometrics, dynamic stabilization, strength, and feedback-driven technique training, are the most effective means of training with youths (Myer et al., 2013).

2.5 Research Hypothesis

Given the current ACL epidemiology, the necessity to determine whether or not neuromuscular training can reduce ACL injury risk in pre-pubescent females appears to be essential (Ford, Sharprio et al., 2010: Hewett et al., 2006a: Myer et al., 2009). Evidence suggests that implementing such programmes before neuromuscular deficits occur, may be the optimal time to improve lower limb biomechanics that are associated with ACL injury (Myer et al., 2013: Quatman-Yates et al., 2013). Therefore, this study aims to examine the effects of an 8-week integrated neuromuscular programme on ACL injury risk in pre-pubescent gymnasts. The hypothesis of the study is that the integrated neuromuscular programme will reduce ACL injury risk in the training group.

CHAPTER 3

METHOD

3.1 Participants

The level of the gymnasts was previously determined by training status, defined by years of gymnastic experience and hours trained per week (Lefevre et al. 2012). In order to be eligible for the study, each participant had a minimum of one year's gymnastic experience and trained between six and 20 hours per week. The study used a sample of 36 females aged six to twelve, all from a local artistic gymnastics club. Studies that have used field based protocols have previously used similar sample sizes to examine adaptations to INT programmes with youths (Faigenbaum et al. 2011). The participants were organised into an experimental group (n=16) and a control group (n=16). Gymnasts were assigned to each group according to the days they trained. All gymnasts attended a familiarisation session prior to baseline testing. *Figure 2* demonstrates the protocol of this study.

Informed consent and assent was obtained prior to the study from each parent and child. Permission for the study was granted by the Cardiff Metropolitan ethical committee.

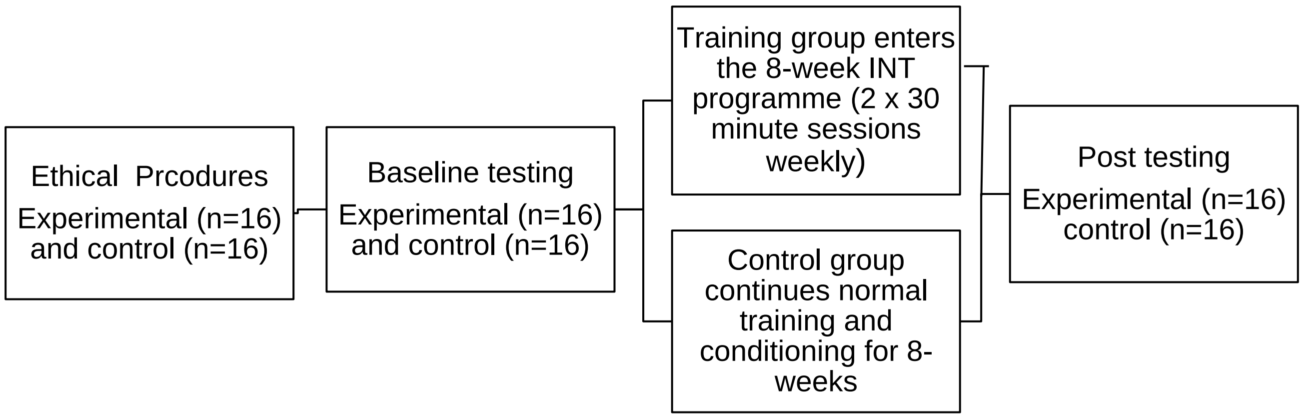

Figure 2. The protocol for the training and control groups

3.2 Procedures

Physical characteristics were recorded prior to testing to include the gymnast's age, body mass (0.1 kilograms), standing and sitting height (0.1 centimetres), using weighing scales and a portable stadiometer. Each gymnast's chronological age was additionally recorded in years and months. The gymnasts' anthropometric measures are shown in *Table 1*. Functional leg dominance was determined using three protocols previously used by Hoffman et al. (1998): ball kick, step and balance recovery. The dominant leg for each test was identified as the leg used most often in three trials (Hoffman et al., 1998).

Table 1. Anthropometric measures for the training and control groups

Group	Age (yr)	Body mass (kg)	Standing height (cm)	Seated height (cm)	Maturity offset (yr)	APHV
Training	8.2 ± 1.7	26.1 ± 5.1	127.0 ± 10.0	68.5 ± 5.3	-3.4 ± 1.4	11.6 ± 0.4
Control	10.0 ± 1.2*	30.8 ± 5.4*	134.0 ± 9.2*	70.4 ± 4.1	-2.1 ± 1.0*	12.1 ± 0.4*

*significant difference ($P < 0.05$)

Both groups of gymnasts underwent the same battery of tests at the beginning and end of the 8-week programme. Gymnasts performed all tests barefoot wearing a leotard. The tests were performed at the beginning of training following the gymnasts' usual warm up. The same coaches administered each protocol pre and post, to increase standardisation. The participants were organised into three testing groups according to the days they trained, to allow for testing to take place over two days. The fundamental movement screening and the sub-maximal hopping test were performed on the first day of testing, followed by the trunk endurance holds and lower limb TTS on the second. The test protocols chosen have been previously reported in youth-based literature and are shown in *Table 2* (Lloyd et al., in press: Lloyd et al., under review: Lloyd et al., 2009).

Table 2. Battery of Tests

Variable	*Test and measure*	*Equipment*
Deep squat	*Functional mobility/stability of the hips, knees and ankles*	*FMS test kit*
In-line lunge	*Torso, shoulder, hip, knee, ankle stability/mobility*	*FMS test kit*
Trunk strength endurance	*Maximal flexion and extension hold*	*Stop watch, table*
Leg stiffness	*Sub-maximal hopping*	*Contact mat, metronome*
TTS	*Drop jump followed by a held unilateral landing*	*Force plate, 20cm block*

3.2.1 Core Strength Endurance Tests

To assess core endurance strength, each gymnast performed a trunk extension and flexion hold until failure, as shown in *Plates 1 and 2*. This isometric test has previously been used by gymnastic coaches to monitor muscular strength endurance (Arkaev et al., 2004). It has also been used to examine the effects of a 10-week trunk programme on low-back pain in gymnasts (Durrall et al., 2009). The gymnasts performed a single trial, where maximum time held was recorded using a stop watch to the nearest 0.1 of a second. To reduce testing bias, subjects were not informed of their results following baseline testing, and prior to post testing (Durall et al., 2009).

Plate 1. Trunk extensor hold test

Plate 2. Trunk flexor hold test

3.2.2 Movement Competency Screening

FMS tests were incorporated in the study to assess the gymnasts' quality of movement during simple movement patterns, to reveal any muscular imbalances or compensatory movements (Cook et al., 2006a). The deep squat and the in-line lunge protocols were chosen for the study as they have recently been significantly correlated to measures of physical performance in youths (Lloyd et al. in press). Both FMS tests were assessed following the protocol described by Cook et al. (2006a) and Cook et al. (2006b). Each gymnast performed three trials of each movement screen (bilaterally where appropriate) and all data collected was recorded. Guidelines for scoring were followed in line with Cook et al. (2006a): Cook et al. (2006b), with the highest trial score recorded for analysis.

3.2.3 Leg Stiffness Test

Leg stiffness was measured using the equation proposed by Dalleau et al. (2004 [equation 1]) using the sub-maximal hopping protocol on a portable contact mat, a test shown to be valid with youth populations (Lloyd et al., 2009). Each gymnast performed one trial of 20 consecutive hops, at a frequency of 2.5 Hz which was maintained via a quartz metronome (Lloyd et al., 2009: Lloyd et al., under review). The gymnasts were instructed to keep their hands on their hips and bounce (a term used to allow them understand the need to keep their legs extended when making contact with the mat). The gymnasts were permitted one practise to familiarise themselves with the protocol and, specifically, the tempo of the metronome. All contact mat data was then collected via an iPAQ and later exported as an Excel file ready for analysis. Variables used in the study for analysis included: contact time, flight time, absolute leg stiffness and relative leg stiffness.

Leg stiffness = $[M*\pi(Tf+Tc)]/Tc2[(Tf+Tc/\pi)-(Tc/4)$ [equation 1]

3.2.4 Time to stabilisation test

TTS has previously been used to assess neuromuscular control and postural stability, through measuring an athlete's ability to land statically from a dynamic drop jump (Flanagan et al., 2008). Each gymnast performed a drop jump from a 20 centimetre height onto a force plate to land unilaterally. The force plate calculated the time taken for a gymnast's vertical ground-reaction forces to stabilise once they had landed from a jump, within five percent of their body weight (Flanagan et al., 2008). The arm position was standardised to the position the gymnasts consistently use to land during their training.

Each gymnast was afforded three practises to familiarise themselves with the protocol, as Flanagan et al (2008) noted a greater habituation period was needed to increase reliability. Two successful trials were recorded per leg for each gymnast. The following variables were collected from the force plate for TTS analysis: vertical ground-reaction force, contact time, flight time and body mass.

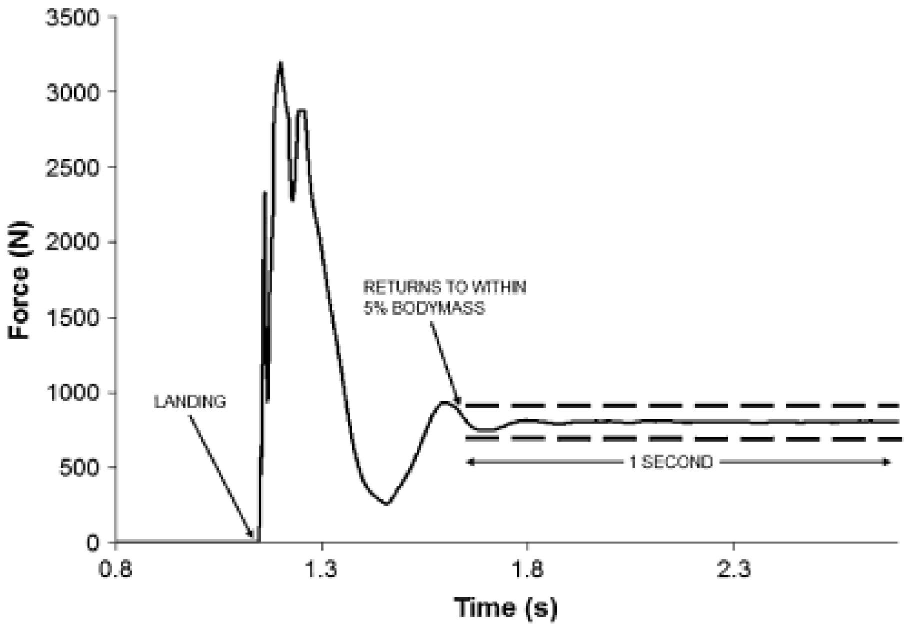

Figure 3. Illustrates the vertical ground-reaction force traces and action points used to calculate time to stabilization during the landing phase of the plyometric depth jump (Flanagan et al., 2008)

3.3. Training Programme

Following the battery of tests, the experimental group participated in an INT programme specifically designed for competitive young gymnasts. The programme consisted of two weekly sessions lasting approximately 35 minutes each, for a duration of 8 weeks. The programme was carefully supervised throughout by at least two qualified gymnastic coaches at all times, and a trainee strength and conditioning coach. The INT programme design was multidimensional (including dynamic stabilization, fundamental movement skill development, resistance training) and based on previous youth literature that had highlighted the most effective types of training modalities in injury prevention programmes (Myer et al., 2011: Myer et al., 2013). The programme was also based on Lloyd and Oliver’s (2012) Youth Physical Development (YPD) model, which emphasises the importance of prioritising muscular strength at all stages of athlete development.

Each session commenced with the gymnasts' usual warm up, to elevate core temperature and reduce the risk of injury. The content of the sessions was divided into three sections: core conditioning (14% of total session time), movement preparation (43%) and basic resistance training exercises (43%). The time spent on each of the three areas was consistently maintained throughout the intervention. Intensity was increased over the 8-week duration through the use of resistance in the form of: body weight, resistance bands, medicine balls and free weights. Such equipment has been successfully used in youth resistance programmes to bring about physiological adaptations and enhance performance (Lloyd et al., 2014).

3.3.1 Core Conditioning

The first five minutes of each session was performed as a group and involved a variety of core strengthening exercises targeting the abdominals (rectus abdominis, transverse abdominis, internal and external obliques), trunk (erector spinae, quadratus lumborum) and hip (gluteus maximus, gluteus medius, psoas major, hamstrings). These muscle groups have been highlighted as fundamental in other INT programmes (Faigenbaum et al., 2011).

3.3.2 Movement Preparation

The following 10 minutes of the session focussed on movement preparatory skills commonly used within gymnastics. These included landing, rebounding, hopping and jumping, as well as strengthening exercises (clams, bridging, Nordic eccentric hamstring drops) that underpin these movements. Lloyd et al. (2014) highlight the necessity of including a range of strengthening exercises to develop motor skill competency in youths. This section of the session was often performed as ‘lines’ that is, repeating the exercise across the floor, a standard gymnastic coaching practice. Emphasis was placed on correct biomechanics during each of the repetitions, in order to encourage the safe execution of skills. For example, landings with appropriate knee flexion while avoiding knee valgus or varus rotation. Youth friendly coaching cues, such as ‘quiet landings’, ‘knees track toes’ etc. were used to encourage correct technique.

3.3.3 Basic Resistance Training

The resistance training concentrated on addressing the gymnasts' lower body force expression and technical competency through both unilateral and bilateral exercises. The outline of the programme design is illustrated in *Tables 3, 4, 5 and 6* below. Youth specific resistance training guidelines were followed to reduce injury risk and promote athlete development (Lloyd et al. 2012). The programme used resistance in the form of body weight to encourage correct technique during basic exercises such as squatting and lunging. If further resistance was required, child-sized equipment was used such as light weighted dumbbells and bars. The resistance exercises increased in complexity as the INT programme progressed, promoting technical competency for future resistance training. For example, the front squat in week one was progressed to the overhead squat in week two.

Table 3. Training programme weeks 1 and 2

Time (mins)	Competency type Exercise	Week 1		Competency type Exercise	Week 2	
5	Core Conditioning	S1	S2	Core Conditioning	S3	S4
	Dish conditioning set			V-sit conditioning set		
	Arch conditioning set			Dish conditioning set		
	Plank conditioning set			Front support conditioning set		
	Front support holds (with variations)			Handstand holds		
15	Movement preparation	S1	S2	Movement preparation	S3	S4
	Inch worms			Single leg bridging		
	Bridging			Clams		
	Rebounds (stiff legs)			Rebounds (stiff legs)		
	Countermovement jumps with correct landing shape (quiet)			Countermovement jumps (quiet landings and MRB)		
	Broad jumps(quiet landings)			Broad jumps(quiet landings and MRB)		
15	Basic resistance training	S1	S2	Basic resistance training	S3	S4
LB Bilateral	Front squat	2x10	2x10	Overhead squat (holding dowel)	2x10	2x10
	Squat jump onto block	2x10	2x10	Squat jump onto block (MRB)	2x10	2x10
LB Unilateral	Single leg lunges	2x10	2x10	Single leg lunges	2x10	2x10
	Rock back and stand up	2x5	2x5	Rock back and stand up	2x5	2x5

Table 4. Training programme weeks 3 and 4

Time (mins)	Competency type Exercise	Week 3		Competency type Exercise	Week 4	
5	Core Conditioning	S5	S6	Core Conditioning	S7	S8
	Extension holds/ lifts			Dish conditioning set		
	Flexion holds			Arch conditioning set		
	Front support holds (with variations)			Front support holds (with variations)		
15	Movement preparation	S5	S6	Movement preparation	S7	S8
	Monster walks (resistance bands)			Single leg bridging and holds (MRB)		
	Single leg bridging and holds (MRB)			Clams (MRB)		
	Rebounds (stiff legs)			Rebounds (stiff legs)		
	Skipping legs straight (rebounds)			Single leg hops to stick (quiet landing)		
	From two feet, jump to land on a single leg			Hop in a zigzag pattern and stick		
15	Basic resistance training	S5	S6	Basic resistance training	S7	S8
LB Bilateral	Squats with medicine ball	3x5	3x5	Squats jumps with medicine ball	3x5	3x5
	Drop jump to stick landing	3x5	3x5	Drop jump to stick landing	3x5	3x5
LB Unilateral	Single leg lunges (dumbbells)	3x5	3x5	Single leg lunges stood on bench	3x5	3x5
	Rock back stand up	3x5	3x5	Single leg lunges (dumbbells)	3x5	3x5

Table 5. Training programme weeks 5 and 6

Time (mins)	Competency type Exercise	Week 3		Competency type Exercise	Week 4	
5	Core Conditioning	S9	S10	Core Conditioning	S9	S10
	V-sit conditioning set			Extension holds/ lifts		
	Dish conditioning set			Flexion holds		
	Handstand conditioning set			Plank conditioning set		
15	Movement preparation	S9	S10	Movement preparation	S9	S10
	Abductor leg lifts foot pointing down (MRB)			Abductor leg lifts/holds foot pointing down (MRB)		
	Abductor leg lifts foot pointing up (MRB)			Abductor leg lifts/holds foot pointing up (MRB)		
	Rebounds (stiff legs)			Rebounds (stiff legs)		
	Hop to face different directions and stick			Hop, hop, hop to stick landing		
	Hop, hop, hop to stick landing			Lateral hops to stick		
15	Basic resistance training	S9	S10	Basic resistance training	S9	S10
LB Bilateral	Squats with medicine ball	3x5	3x5	Squats with medicine ball	4x6	4x6
	Overhead squat (weighted bar)	3x5	3x5	Overhead squat (weighted bar)	4x6	4x6
LB Unilateral	Single leg lunges stood on bench	3x5	3x5	Single leg lunges (dumbbells)	4x6	4x6
	Drop jump to land single leg	3x5	3x5	Drop jump to land single leg	4x6	4x6

Table 6. Training programme weeks 7 and 8

Time (mins)	Competency type Exercise	Week 7		Competency type Exercise	Week 8	
5	Core Conditioning	S13	S14	Core Conditioning	S15	S16
	Dish conditioning set			V-sit conditioning set		
	Arch conditioning set			Dish conditioning set		
	Front support holds (with variations)			Handstand holds		
15	Movement preparation	S13	S14	Movement preparation	S15	S16
	Single leg bridging and hold set, foot raised (MRB)			Single leg bridging and hold set, foot raised (MRB)		
	Clam set (MRB)			Abductor leg lifts foot neutral (MRB)		
	Rebounds (stiff legs)			Rebounds (stiff legs)		
	Maximal length rebounds			Maximal length hops (rebounds)		
	Unilateral landings competitions			Unilateral landings competitions		
15	Basic resistance training	S13	S14	Basic resistance training	S15	S16
LB Bilateral	Squats with medicine ball	4x6	4x6	Squats with medicine ball	4x6	4x6
	Squat jumps	4x6	4x6	Squat jumps	4x6	4x6
LB Unilateral	Drop jump to land single leg in different directions	4x6	4x6	Single leg lunges (dumbbells)	4x6	4x6
	Rock back and stand up hop	4x6	4x6	Drop jump to land single leg in different directions	4x6	4x6

3.4 Statistical Analyses

Descriptive statistics (means and standard deviations) were calculated for pre and post intervention data through Microsoft Excel. A 2 x 2 (group*time) repeated measures analysis of variance (RMANOVA) was used to determine the existence of any differences in all variables tested. 'Group' represents the training and control subgroups, whilst 'time' refers the pre and post intervention data. Sphericity of data was tested by Mauchly's statistic, and where violated, a Greenhouse-Geiser adjustment was used. Bonferroni and Games-Howell post hoc tests were used to determine the origin of any between-group differences, when equal variance was or was not assumed respectively. Partial eta squared values were also used to assess the main size effects of the findings. Median values and percentages of individual scores from the FMS data were calculated via Microsoft Excel. All remaining analysis was computed using SPSS (v.20) for Windows.

CHAPTER 4

RESULTS

4.1. Movement Competency Results

The median values and the distribution of the individual FMS scores are presented in *Tables 7 (training) and 8 (control).* The training group demonstrated improvements in median values in all of the FMS tests following the training intervention. The distribution of the control group's individual FMS scores show improvement. However, the median values of the pooled data remained the same.

Table 7. Training group's pre- and post-data for FMS

Variable	Training Group	
	Pre	Post
Deep OH squat	1 (1=56%, 2=19%, 3=25%)	2 (1=0%, 2=56%, 3=47%)
In-line lunge (dominant)	1 (1=63%, 2=25%, 3=12%)	2 (1=25%, 2=50%, 3=25%)
In-line lunge (non-dominant)	1 (1=75%, 2=6%, 3=19%)	2 (1=12%, 2=63%, 3=25%)

significant change from baseline measurement (*P* < 0.05)

Table 8. Control group's pre- and post-data for FMS

Variable	Control Group	
	Pre	Post
Deep OH squat	2 (1=31%, 2=38%, 3=31%)	2 (1=6%, 2=56%, 3=38%)
In-line lunge (dominant)	2 (1=19%, 2=50%, 3=31%)	2 (0=6%, 1=6%, 2=50%, 3=38%)
In-line lunge (non-dominant)	2 (1=44%, 2=37%, 3=19%)	2 (1=19%, 2=44%, 3=37%)

*significant change from baseline measurement (*P* < 0.05)

4.2 Leg Stiffness Results

The training group's results from the sub-maximal hopping test show a trend of increased absolute and relative leg stiffness measures indicating improvement, although this was not significant. However, a significant decrease in both of these measures was seen in the control group. Contact time significantly increased for the control group, whilst the training group's values were unchanged. Means (±SDs) for all variables collected during the sub-maximal hopping test pre and post are shown in *Tables 9 (training) and 10 (control).*

Table 9. Training group's pre- and post-data for contact time, flight time, absolute and relative leg stiffness

Variable	Training Group		Pre- to post- change effect size (eta^2)
	Pre	Post	
Absolute leg stiffness ($kN \cdot m^{-1}$)	20.6 ± 4.4	21.2 ± 4.6	0.009
Relative leg stiffness	46.6 ± 8.5	48.1 ± 10.0	0.010
Contact time (s)	0.14 ± 0.03	0.13 ± 0.02	0.024
Flight time (s)	0.26 ± 0.03	0.26 ± 0.02	0.001

*significant change from baseline measurement ($P < 0.05$)

Table 10. Control group's pre- and post-data for contact time, flight time, absolute and relative leg stiffness

Variable	Control Group		Pre- to post- change effect size (eta^2)
	Pre	Post	
Absolute leg stiffness ($kN \cdot m^{-1}$)	24.1 ± 4.9	20.0 ± 4.4*	0.302
Relative leg stiffness	49.6 ± 8.7	40.3 ± 8.6*	0.275
Contact time (s)	0.14 ± 0.01	0.15 ± 0.01*	0.151
Flight time (s)	0.26 ± 0.02	0.27 ± 0.03	0.049

*significant change from baseline measurement ($P < 0.05$)

4.3 Stabilisation Results

There were significant decreases in TTS for the non-dominant leg of both groups. Additionally, there was a significant reduction in TTS for the dominant leg in the control group (P = 0.04). There was a non-significant reduction in TTS for the dominant leg in the training group, though this difference was approaching significance (P = 0.09). The training group's flexion and extension endurance hold times significantly improved (flexion P= 0.02 and extension P = 0.04), whilst the control group's showed no significant difference. *Tables 11 (training) and 12 (control)* show all of the stabilisation results.

Table 11. Training group's pre- and post-data for stabilisation screening

Variable	Training Group		Pre- to post- change effect size (eta^2)
	Pre	Post	
TTS dominant (s)	1.21 ± 0.5	0.86 ± 0.7	0.091
TTS non-dominant (s)	1.23 ± 0.6	0.75 ± 0.3*	0.006
Max extension hold (s)	75.3 ± 45.2	107.8 ± 51.9*	0.337
Max flexion hold (s)	105.3 ± 71.6	185.1 ± 95.7*	0.388

*significant change from baseline measurement (*P* < 0.05) Note: TTS Dominant (Training group P = 0.09)

Table 12. Control group's pre- and post-data for stabilisation screening

Variable	Control Group		Pre- to post- change effect size (eta^2)
	Pre	Post	
TTS dominant (s)	1.47 ± 0.7	1.02 ± 0.8*	0.139
TTS non-dominant (s)	1.59 ± 0.7	0.96 ± 0.5*	0.001
Max extension hold (s)	90.7 ± 25.9	95.1 ± 20.4	0.001
Max flexion hold (s)	117.8 ± 49.5	128.3 ± 60.0	0.011

*significant change from baseline measurement (*P* < 0.05)

CHAPTER 5

DISCUSSION

5.1 Main Findings

Previous research has demonstrated the effectiveness of INT programmes on ACL injury risk measures in young females with a games-specific background (Myer et al., 2008: Myer et al. 2013). Though evidence suggests the optimal time to implement INT programmes with females is prior to the onset of puberty, the training adaptations of such programmes on child athletes is still under researched. Therefore, the effects of an INT intervention on pre-pubescent gymnasts' core strength, movement competency, leg stiffness and TTS remained unclear.

The main findings of the study were that an 8-week INT programme significantly increased core strength and maintained leg stiffness measures in pre-pubertal female athletes. Interestingly, there were significant decrements in the control group's absolute and relative stiffness measures, due to longer contact times. As both groups were in a competitive phase of training, this suggests the intervention had a maintenance effect for the participants in the INT group. Additionally, the results revealed a greater improvement in movement competency in the training group. These results displayed greater increases in median values of individual FMS scores and overall distribution than in the control group. Finally, stabilisation results demonstrated significant improvements in TTS in both groups' non-dominant leg. Each group reduced their TTS on their dominant leg however, unexpectedly, this decrease was only significant in the control group.

5.2 Core Strength Endurance

Participants in the INT group made a significantly greater improvement in maximum flexion and extension holds, as compared with the control group. Previous research has emphasised the importance of developing core neuromuscular control in young females, to regulate their lower extremity during high velocity activities (Myer et al., 2008: Hewett & Myer, 2011). More specifically, the core acts as a critical modulator by pre-activating trunk and hip stabilisers (Myer et al., 2008). This counterbalances any lateral trunk motion, thus keeping lower limb alignment and reducing ACL injury risk (Myer et al., 2008). However, during peak height velocity, anatomical mechanisms (rapid growth of the femur and tibia, and a gain in mass) cause an increase in centre of mass height (Myer et al., 2008). These changes make it more difficult for the trunk and hip musculature to control and balance the lower extremity during dynamic tasks (Myer et al., 2008). Myer et al. (2008) found neuromuscular training targeting the trunk was effective in female adolescents. The intervention was found to improve lower limb biomechanics by reducing knee abduction loads and increasing lower extremity control (Myer et al., 2008). Similarly, in the current study, the training group's lower limb movement competency improved when performing functional movements, such the overhead squat and the in-line lunge.

Only five minutes of each INT session were spent on 'core conditioning' exercises, yet the improvements in these measures were significant. Interestingly, Faigenbaum et al. (2011) also included just one exercise to specifically increase core strength, but found that the children following the INT programme improved notably in the abdominal curl-test. Unlike in most other sports, core conditioning and body shaping are a critical part of a gymnast's development programme from an early age (Durallet al., 2009). Improvements in the training group could therefore be attributed to the greater demands for core control during other aspects of the programme, for example in functional movements and resistance training exercises. Evidence suggests greater muscle activation of the lumbopelvic hip complex occurs during athletic movements, compared with traditional core stability exercises (Oliver et al., 2010). In addition, core exercises that increase motor control functionally, may be more transferable to athletic performance (Oliver et al., 2010).

The findings of the present study therefore suggest that incorporating functional kinetic chain movements, could enhance core control further, and consequently reduce injury risk during dynamic tasks (Oliver et al., 2010). Implementing programmes that increase core strength and stability prior to the onset of puberty, may induce a neuromuscular spurt to address any deficits that can accelerate during maturation, reducing injury risk (Myer et al., 2008: Hewett & Myer, 2011). Future research is needed to assess the effects of such programmes on female athletes' long term physical performance and injury risk profile.

5.2 Movement Competency

Previous research suggests that childhood is the optimal time to develop correct movement patterns, in order for athletes to be more effective later in adolescence when performing complex and gross skills (Lloyd & Oliver, 2012). Faigenbaum et al. (2011) demonstrated that an INT programme with primary school children was effective in improving functional movement skills and physical fitness. Interestingly, the study found 7-year old girls to be more sensitive to the INT training than the boys (Faigenbaum et al., 2011). This suggests there could be an optimum sex-specific window of opportunity for such programmes in children (Faigenbaum et al., 2011: Faigenbaum et al., in press: Myer et al., 2013). However, few studies have established the effectiveness of these programmes on youth athletes with sports-specific training background (Behringer et al., 2011).

This study has shown that an 8-week INT programme can successfully enhance movement competency in children with previous training experience. The training group's FMS median values for each test increased from 1 to 2 following the INT programme, whilst the control group's median did not change. Although the difference in median values of the training group were not large, the individual distribution of scores within the FMS testing system increased, suggesting the programme was effective in developing movement competency across the group.

Notably, the pooled data of both groups' baseline FMS scores revealed that the highest percentage of individual scores for each test was 1. Of concern is that the cohort of subjects were competitive gymnasts, already performing relatively complex skills. Despite this, the results indicate that the gymnasts' ability to perform simple movement patterns correctly was low, consequently increasing their injury risk (Cook. et al., 2006a). Research across other sports has confirmed that children who specialise in a single sport before puberty, become underdeveloped in gross motor skills (Mostafavifar et al., 2013). These results suggest that the gymnasts have developed competency in sports-specific movements, as opposed to attaining a wide vocabulary of movement. As gymnasts frequently end their competitive careers before the age of 20 (Erlandson et al., 2007), their lack of multi-dimensional motor skills may limit their options for long-term participation in physical activity (Mostafavifar et al., 2013). Furthermore, 50 percent of all injuries seen in paediatric sports medicine are overuse type injuries (Dalton, 1992), indicating an imbalanced training programme. Other implications include the possible development of Burnout Syndrome in young athletes, which could also deter long term participation in sport (Mostafavifar et al., 2013). Given the current concerns over early sport specialisation in young athletes, the results highlight the need for coaches involved in these sports to monitor and address FMS development throughout childhood.

As the content of the INT programme in this study targeted multiple components, the improvements in FMS could be attributed to a number of factors. Since the ability to perform functional movement skills successfully is underpinned by muscular strength (Lloyd & Oliver, 2012), the greater improvement in FMS results could be explained by the significant increases in trunk strength. It is also possible that the INT group's movement competency was developed as a result of increased proprioception and balance ability. Specifically, the uni-lateral aspects of the programme, such as the single leg resistance exercises and landing practise, could have increased the training group's lower limb postural control (Myer et al., 2005). Furthermore, a recent meta-analysis reported programmes that incorporate balance and other types of training, are most effective in reducing injury risk in youth athletes (Myer et al., 2013).

5.4 Leg Stiffness

The findings of the present study revealed leg stiffness measures remained unchanged in the training group, though with a trend of increasing. There are a number of possible explanations for these results. It is conceivable that programmes that aim to increase leg stiffness in young athletes are age sensitive. This is in line with other research, which found significant improvements in leg stiffness following a 4-week plyometric programme in 12 and 15 year old males, but no significant improvements in the 9 year old age group (Lloyd et al., 2012). The authors proposed that as older youth athletes have a greater body mass, they develop more overall leg stiffness to maintain their center of mass displacement when making contact with the ground (Lloyd et al., 2012). It could therefore be argued that had the gymnasts in the study been adolescents, they may have shown a greater improvement in leg stiffness. However, as noted above, as the risk of ACL increases following puberty (Ford, Myer et al. 2010), the value of implementing INT programmes with pre-pubescent athletes is evident. Additionally, despite a lack of significant improvement in leg stiffness, we observed an enhancement in the gymnasts' mechanical ability. This is further evidenced by the training group's greater advance in functional movement competency, compared with the control. It is therefore feasible that a longer training intervention could have increased stiffness measures in this population.

Furthermore, the gymnasts in the present study were in a competitive phase of training, and so subjected to accumulative fatigue. It is therefore probable that greater gains in leg stiffness could have been attained in a preseason block of training. It must also be noted that due to the nature of the sport, gymnasts are already engaged in developing leg stiffness, as they routinely perform skills such as tumbling, rebounding and leaping. Consequently, it could be hypothesised that an 8-week INT programmes may achieve greater gains in leg stiffness in young novice athletes, or athletes from other sports.

In the control group, in contrast, the results of the study showed a significant decrease in absolute and relative leg stiffness measures, as a result of increased contact times. Of note, is that the main effects of significance were small to moderate. Recently, the effects of a soccer-specific fatigue protocol on leg stiffness was investigated in females across three different age groups (U13, U15 and U17) (Lloyd et al., under review). The study found that stiffness was reduced in the youngest age group, but maintained (U15) and increased (U17) in the older two, suggesting females' response to fatigue differs during the stages of maturation (Lloyd et al., under review). As all of the participants in the current study were all under the age of 13, it is possible that the decrements seen in the control group were due to accumulated fatigue, following a competitive phase of training. A reduction in lower limb stiffness may decrease young athletes' ability to stabilise their knees during dynamic tasks, consequently placing them at greater risk of an ACL injury (Lloyd et al., under review). Fatigue may cause neuromuscular changes in the musculo-tendon unit, due to a reduction in pre-activation before ground contact and an increase in co-contraction afterwards (Lloyd et al., under review).

The results therefore indicate that an 8-week INT programme was effective in maintaining leg stiffness in pre-pubertal athletes, throughout a competitive phase of training, where accumulative fatigue is possible. Coaches should be aware of the possible effects of fatigue in child athletes during this phase of the season, and aim to target these deficits with appropriate plyometric exercise prescription.

5.5 Stabilisation

TTS quantifies athletes' neuromuscular control and postural stability during landing tasks from plyometric exercise (Wikstrom et al., 2004). Those able to stabilise more quickly may be less at risk of ACL tears. This study's TTS results for the training group showed a significant decrease in TTS for the gymnasts' non-dominant leg. There was also a reduction in TTS for their dominant leg, but not a significant decrease, although it was approaching significance (P=0.09). The INT programme was therefore effective in improving gymnasts' ability to stabilise more quickly on their non-dominant leg, during landing tasks. A more equal TTS on both legs may reduce ACL injury risk in young athletes. It is noteworthy that the young gymnasts were already fully aware of which was their 'good' or 'bad' leg when landing. Gymnasts begin to develop a dominant leg from an early age, as many skills require a lead leg for take-off, tumbling and landings. As mentioned above, it is important for child athletes in early specialisation sports, to develop a diverse set of motor skills to reduce injury risk (Mostafavifar et al., 2013).

Unexpectedly, the control group's TTS results revealed a significant decrease in TTS for both the dominant and non-dominant leg. However, the main effect of significance was 0.1, suggesting improvements seen in the TTS of the control group were small. The results also show relatively large standard deviations across most of the TTS data, implying the variance in values was high. With these factors in mind, it is important to note that this study was novel in using the TTS protocol with children. Flanagan et al. (2008) found their TTS protocol using bilateral landings to be unreliable with adults. They suggested that as each participant was only afforded one trial, with a greater period of habituation, reliability could have increased. The participants in the current study, however, were given three practises but were required to land unilaterally. It is therefore reasonable to suggest that the TTS protocol might have been too difficult for the children to familiarise themselves with. Furthermore it was observed that the young gymnasts were cognitively aware of the importance of 'sticking' their landings. This appeared to impede their ability to jump as fast and as high as they could, reducing the reliability and validity of the protocol.

This potentially highlights an opportunity for future research to develop an appropriate protocol for TTS in youth populations. Flanagan et al. (2008) proposed that TTS measures could assess the extent of the role balance plays in stabilising athletes on landing, as well as quantifying the intensity of different plyometric exercises. This knowledge could be particularly valuable to coaches involved in training youths, as misconceptions regarding the safety of using plyometrics as a modality with children appears still to be an concern for some (Lloyd et al., 2011).

5.6 Practical Applications

Overall, the study has shown how the implementation of an 8-week INT programme could benefit pre-pubertal female athletes' injury profile, in an early specialisation sport. Coaches should be aware that incorporating such programmes twice a week, for just 35 minutes, can improve core strength and movement competency, as well as maintain leg stiffness in pre-pubertal athletes during a competitive phase. Training interventions that successfully enhance movement competency in child athletes (particularly those in early specialisation sports) and encourage the development of a wide range of motor skills, increase the likelihood of long term participation in physical activity. Furthermore, INT programmes that reinforce correct lower limb biomechanics and movement patterns in athletes from a young age, as well as aid in the resistance of accumulative fatigue, may reduce the risk of ACL injuries occurring. Such a serious injury may result in the premature end of a career, the early onset of osteoarthritis or deter athletes from participating in sport long term. It must also be acknowledged that athletes that remain injury free for long periods, may gain greater adaptations from training and enhance performance. The wider application of neuromuscular interventions may be effective in reducing ACL injury in youth athletes across a range of other sports programmes.

CHAPTER 6

CONCLUSION

6.1 Overview of Findings

The study has provided evidence to suggest that an integrated neuromuscular training programme which targets several components, such as core strength, leg stiffness, movement competency and TTS, can produce positive training outcomes which could reduce the risk of ACL injury in young gymnasts. Exposing child athletes to training programmes that encourage correct lower extremity biomechanics, increase strength and improve overall movement competency, can improve a number of risk factors associated with ACL injury. Coaches who work with paediatric populations (particularly females) should note that the implementation of such programmes before the onset of puberty, could induce a neuromuscular spurt, which consequently reduces injury risk during adolescence (Ford, Myer et al., 2010). This study has indeed revealed several potential benefits for pre-pubescent female gymnasts, following an 8-week neuromuscular training intervention:

- A significant improvement in core strength, increasing control of the lower extremity, and reducing knee abduction loads during dynamic tasks (Ford, Sharprio et al. 2010).
- Improved lower limb movement competency, addressing compensatory movements that may lead to poor biomechanics, and as a result, predispose athletes to injury (Cook et al., 2006a).
- Maintained leg stiffness measures during a competitive phase of training (where accumulated fatigue is possible), enabling athletes to be more efficient at tolerating loads and regulating forces when landing, thus reducing their risk of ACL injury (Ford, Sharprio et al. 2010).

6.2 Limitations

Although all the participants in the study were pre-pubescent, the training and control group were found to be significantly different in terms of chronological age (training 8.2 ± 1.7 and control 10.0 ± 1.2*). However, as the groups were organised according to the days they trained on, this was unavoidable. Another possible limitation was that the INT programme was not sufficiently individualised for all the participants within the training group. This was as a result of large group sizes with varying ages and abilities, which made it more difficult to accommodate the athletes' progression individually. Taking these factors into consideration, two sub-groups within the INT group could have shown further improvements. The most effective neuromuscular training programmes with young athletes include individually prescribed exercises, sets, and repetitions that are modified continuously (Myer et al., 2013). However, the logistics of the gymnasts' training schedules and absence of additional experienced strength and conditioning support, made this unpractical. Finally, as the training group only maintained their leg stiffness, the use of a portable contact mat to provide real time feedback, may have allowed a better monitoring of the gymnasts' progression. With this knowledge, the gymnasts could have been stimulated further with altered exercises that may have increased their leg stiffness.

6.3 Directions for Future Research

The area of research into effective interventions for injury prevention in youth athletes remains understudied. Further study is warranted with paediatric populations, as the benefits of preventing serious ACL injuries are evident. Avoiding the possibility of a premature end to an athlete's sporting career, long term participation (Mostafavifar et al., 2013) and conditions such as osteoarthritis (Fleming, 2003), is clear. Avenues of future research might include:

- What are the effects of INT programmes on female gymnasts' ACL injury risk through maturation? A longitudinal study could enable researchers to further understand the long term benefits resulting from such interventions.
- What are the comparable effects of an INT intervention on male and female pre-pubescent gymnasts' on ACL injury risk? This will reveal if there are any sex-specific differences in responses to INT programmes, and thus enable coaches to individualise their sessions further.
- What are the comparable benefits of INT programme on youth populations over a range of different sports and training experience? This could highlight findings showing different training adaptations in athletes from a variety of sports.

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APPENDICES

APPENDIX A

ETHICS STATUS

Cardiff Metropolitan University | Prifysgol Metropolitan Caerdydd

Date: 17/02/2014

To: Sylvia

Project reference number: 13/7/01U

Your project was recommended for approval by myself as supervisor and formally approved at the Cardiff School of Sport Research Ethics Committee meeting of 26th June 2013.

Yours sincerely

RSL

Supervisor

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