The effect of the Apos Therapy system on knee biomechanics in recreational athletes at risk of a non-contact Anterior cruciate ligament injury

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Abstract

An anterior cruciate ligament (ACL) injury is a catastrophic incident in sports, resulting in an extended period away from athletic participation and even potentially ending a playing career. The disparity between positive laboratory results of neuromuscular training programs and the actual effects on injury outcomes among high-risk populations suggests a missing link in current intervention programs. One proposed explanation for such a gap between laboratory results and incidence outcomes may be related to the time-consuming, complex and difficult implementation of the techniques found to be successful in reducing lower limb movement mechanics and neuromuscular risk factors. A novel option is to explore whether different unstable devices and unstable footwear designs may induce positive biomechanical and neuromuscular effects. The overall aim of this thesis was to determine the effect of an unstable device (AposTherapy system) on knee biomechanics and muscular recruitment patterns while performing functional tasks.

To accomplish the research, four separate trials were conducted separatly. Firstly, a repeatability trial with 11 healthy physically active (male and female) participants was conducted to determine the reliability of the outcome measures for future studies. Secondly, as the AposTherapy system has not previously been trialled within the 'at-risk' female population, a feasibility study investigating whether using the AposTherapy intervention during a six-week period was feasible was conducted. This was followed by a randomised clinical trial amongst 32 female recreational athletes who were indicated to have a high-risk (2D FPPA > 8.4º) indication for sustaining a non-contact ACL injury. Three groups (control and two active intervention groups) were assessed at a six-week outcome point to determine changes in biomechanical outcomes. The results demonstrated positive biomechanical and clinical outcomes specifically in reducing the maximum knee valgus angle during a single leg landing task while only using the AposTherapy system for walking. Furthermore, a significant reduction in maximum hip adduction moments during study tasks was observed when the AposTherapy system use was coupled with additional exercise. The thesis concluded with preliminary study investigating five individuals who were deemed at risk of a second non-contact ACL on their contralateral limb following primary ACL reconstruction (ACLR) surgery. There was a significant reduction in knee valgus angle during the single leg

landing and single leg squat tasks while only using the AposTherapy system for walking in the study with individuals who have had ACLR surgery.

In summary, the results of this thesis showed that the AposTherapy system gave significant improvements in overall stability, with future studies needed to examine a larger-scale application especially in post-ACL reconstruction rehabilitation programs to mitigate the risk of a second ACL injury when athletes return to sport activities. However, more research should also focus on developing more affordable unstable footwear devices which could be incorporated in larger-scale prevention programs in the future.

Chapter One: Introduction

Anterior cruciate ligament (ACL) injuries account for 50% or more of all knee sport injuries (Allan et al., 2013). ACL injury have been increasingly problematic in the lives of both professional and recreational athletes from the physical, psychological and financial perspectives (Lehmann et al., 2017; Sugimoto et al., 2016; Hewett et al., 2013) and are arguably the most disabling serious knee injury associated with sports participation (Paschos et al., 2017; Alarifi et al., 2017; Voskanian et al., 2013; Nordenvall et al., 2012). The majority of ACL injuries (more than 70%) occur in sports during non-contact situations, such as landing from a jump and cutting activities (Olsen et al., 2005; Lim et al., 2009; Hewett et al., 2010; Sugimoto et al., 2012). ACL injuries have been reported as occurring most frequently amongst the young active population during athletic participation such landing, cutting and sudden deceleration while running during volleyball, handball, football and basketball (Renstrom et al., 2008; Mountcastle et al., 2007; Myer et al., 2006; Hewett et al., 2005; Olsen et al., 2004).

The prevalence of ACL injuries around the world has been estimated to be approximately 30 to 84 ACL injuries per 100.000 individuals. Around 30 ACL injuries sustained per 100,000 individuals in the UK (Webb and Corry, 2000), and 32, 37 and 38 ACL injuries per 100,000 individuals in Germany, New Zealand and Denmark, respectively (Singh et al., 2017). Moreover, several countries showed higher incidence rates, according to a study by Domnick et al. (2016), in Sweden, 78 ACL injuries were found to occur per 100,000 individuals. However, ACL injuries are even higher in the United States, with approximately 84 per 100,000 individuals (Bates, et al., 2015). ACL injuries may also lead to significant residual restriction of activity and mobility (Paschos et al., 2017; Lehmann et al., 2017; Alarifi et al., 2017; Smith et al., 2012; Hewett, et al., 2006;). Shah, et al. (2010) reported that, in the United States, nearly 37% of American football athletes were unable to return to their previous level of competition after sustaining an ACL injury. Furthermore, according to a study on handball players in Norway, 42% of players who suffered an ACL injury were not able to return at pre-injury levels, resulting in most players either quitting the sport altogether or continuing to play at a lower level of competition (Myklebust et al., 2003). In another study 50% of Swedish female football players were not able to return to sports following ACL reconstruction (ACLR), whereas, only 15% of the players were able to returne to their pre-injury level of performance (Lohmander et al., 2004,2007).

Additionally, individuals who have previously sustained a non-contact ACL (NCACL) injury and had ACLR surgery showed a higher risk of sustaining a second ACL injury (either graft failure or contralateral injury) compared with individuals who did not sustain a primary ACL injury (Paterno et al., 2010, 2015). Paterno et al. (2014) documented in a study that, overall, 29.5% of athletes suffered a second ACL injury within 24 months of their return to the sport, with 20.5% happening at the contralateral injury and 9% sustaining a graft failure at the ipsilateral side. Moreover, in a systematic review, Wiggins et al. (2016) demonstrated that one in every four athletes who had previously sustained an ACL injury and returned to the same high level of sports will sustain another ACL injury in the return period to play. This high rate of a second ACL injury among young athletes after successful ACLR equals a 30 to 40 times higher injury risk of ACL injury when compared to the uninjured athlete's population (Webster et al., 2014).

Depending on the level of the individual athlete participation in sports, athletes may be classified into either professional or recreational athletes (John et al., 2016). Players who participate in professional club and national teams level were sport is their career are considered professional athletes. On the other hand, players who participate in sports activities for recreational purposes or inter-collegiate events are considered as recreational athletes (John et al., 2016). A systemic review by Lai et al. (2018), reported that rates of return to sports to the pre-injury levels following ACLR are higher among professional athletes (83%, 95%CI 77%-88%), than among recreational athletes (60%, 95%CI 53%-67%). Several studies attribute this difference to several factors such as professional athletes have greater athletic skills (Ardern et al., 2011), superior levels of physical fitness (Lorenz et al.,2013), more advanced knee joint proprioception (Lai et al., 2018), and higher mental profiles (Ardern et al., 2014; Lai et al., 2018). In addition, professional athletes usually have access to high quality healthcare (Koning et al., 2012) and greater financial incentive to play than recreational athletes, which might help to explain why professional athletes have superior rates of returning to competitive levels of sports (Lai et al., 2018; Gupta et al., 2016) at twice the odds compared to recreational athletes (Ardern et al., 2014). Thereby, it is logical to assume that recreactional athletes would be more vunerable to sustaining sports injuries such as ACL injury with less ability to fully recover when compared to professional athletes.

The rates of NCACL injury are reported to be low amongst young children, with no gender disparity observed. However, these rates sharply increase during puberty (LaBella et al., 2014). It has been well documented that female athletes experience a 2–8-fold higher incidence of ACL injuries when compared to male athletes participating in similar sports (Sugimoto et al., 2014; Kijowski et al., 2012; Walden et al., 2012; Hewett et al., 2010). Many factors have been postulated as contributing to ACL injuries, especially amongst female athletes, such as anatomical and hormonal factors, as well as neuromuscular control impairment (Hewett et al., 2006). Alterations in biomechanical and neuromuscular variables have been suggested as potential risk factors of NCACL injuries amongst female athletes (Sugimoto et al., 2012; Yeow et al., 2010; Myer et al., 2009). The altered neuromuscular control and imbalance in muscular recruitment patterns of the lower limb during the execution of sports movements may result in increased lower limb motion and loads, accentuating the risk of NCACL injuries in females (Ford et al., 2003; Mclean et al., 2004; Hewett et al., 2005). If the lower extremities' muscle action controlling the knee joint's dynamic stability do not sufficiently produce the required force, there will be an increase both on the amount of strain on ACL and of the risk of failure (Hewett et al., 2005; Olsen et al., 2004; Mclean et al., 2004). The forces influencing dynamic knee stability can be described as dynamic knee valgus, a combination of rotations and motions among all three main lower limb joints (hip, knee, and ankle joint) (Figure 1-1).

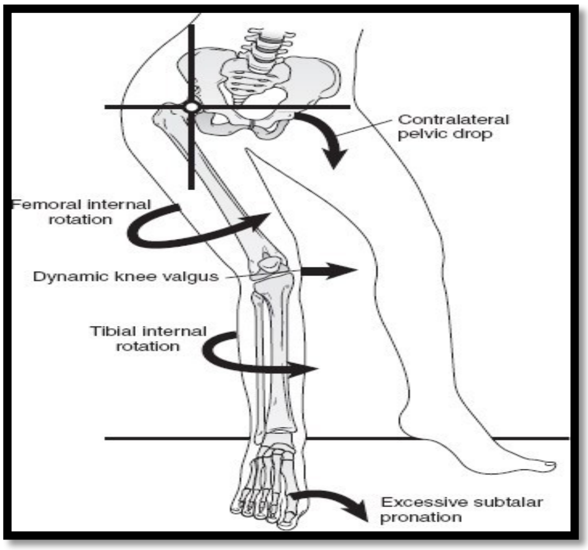


Figure 1- 1: Illustrate biomechanical risk factors for sustaining non-contact ACL injury (Dynamic knee valgus) (Powers et al., 2003).

Studies suggest that a high knee valgus angle and dynamic knee valgus moment during landing or cutting sport manoeuvres are risk factors for sustaining NCACL (Myer et al., 2013; Hewett et al., 2011; Hewett et al., 2005; Ford et al., 2003). Studies that have both observed and analysed the mechanisms of NCACL injuries, indicate that an increase in knee valgus loads is a likely contributor to NCACL injury, as video recordings of NCACL injuries have shown that the knee gives way in the valgus direction prior to and following incidence of the injury (Figure 1-2) (Koga et al., 2010; Krosshaug et al., 2007; Olsen et al., 2004).

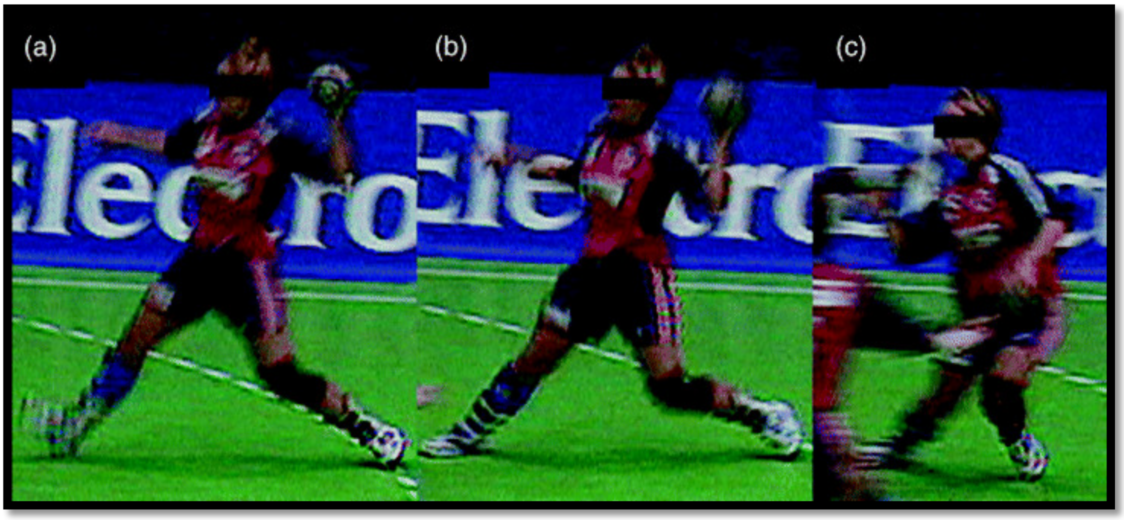


Figure 1- 2: Illustrate Frame sequence of handball player at the time sustaining non-contact ACL injury showing the athlete at (a) initial ground contact, (b) 40 ms and (c)100 ms (Krosshaug et al., 2007).

In addition, studies have indicated that athletes who sustained NCACL had higher knee valgus loads when compared with other athletes during landing tasks in preseason assessment (Chappell and Limpisvasti, 2008; Hewett et al., 2005). Moreover, the combination of valgus loads with anterior draw torques significantly increases the stress on ACL, particularly when the knee is at low flexion angles (Marklof et al., 1995).

Compared with male athletes, female athletes appear to display different knee motion patterns and neuromuscular strategies during the execution of motor tasks in which there is a high risk of an ACL injury (Hewett et al., 2010; Zebis et al., 2008; Hewett et al., 2006; Ford et al., 2003). Female athletes display a tendency to land with a more extended knee position, coupled with an increase in knee valgus angle during athletic movements (Zebis et al., 2008; Lephart et al., 2005; Hewett et al., 2005; Ford et al., 2003). Female athletes have been reported as demonstrating insufficient neuromuscular control while performing landing and cutting sport movements, which may lead to valgus collapse and ACL injuries (Powers et al., 2010; Hewett et al., 2005; Ford et al., 2003).The potential mchanisms underlying the ACL injury rate difference between gender can be attributed to a number of basic categories; anatomical, hormonal, neuromuscler control and biomechanical risk factors (Ford et al., 2003; Hewett et al., 2006). Few if any anatomical variables have been directly link with an increae risk NCACL (Ford et al., 2003). Hormoanal risk factors have been controversial as some studies suggested that sex hormones levels changes during the menstrual cycle play a role in increasing the risk of sustaining ACL injury by altered muscle strength or recruitment pattern and/or reducing the ligament strength due to cyclic changes. However, the finding from several studies regarding the influence if hormones on ACL injury risk are limited and remain controversial (Herzberg et al., 2017; Casey et al., 2014; Lefevre et al., 2013).

Recreational and competitive female athletes who participate in competitive team sports often require sufficient lower limb dynamic stability to withstand the execution of landing and pivoting manoeuvres (Myer et al., 2005). Hence, the incorporation of neuromuscular training (NMT) may help female athletes adopt muscular recruitment strategies to improve knee joint dynamic stability, which in turn, may protect the athlete's ACL from high impulse loads while also enhancing their measures of performances (Monajati et al., 2016; Sugimoto et al., 2016; Michaelidis et al., 2014; Voskanian, et al., 2013). Researchers have suggested implementation of motor control strategies of the lower limbs as a modifiable risk factor for NCACL injury. Therefore, the scholarly focus has been on introducing different neuromuscular intervention programs to improve the risk-laden movement patterns of female athletes during the performance of high-risk manoeuvres (Monajati et al., 2016; LaBella et al., 2014; Voskanian, et al., 2013).

Different training elements have been incorporated such as plyometrics, balance, strength, agility, feedback and education training, resulting in improvements in lower limb movement mechanics or patterns (Hewett et al., 1996; Myer et al., 2005,2006, Chappell and Limpisvasti, 2008; Cochrane et al., 2010; Herrington et al., 2010; Barendrecht et al., 2011; Steffen et al., 2013; Letafatkar et al., 2015; Hopper et al., 2017; Thompson et al., 2017). Moreover, due to modifying the biomechanical risk variables by enhancing neuromuscular control of the lower extremities, improvements in high-risk movement patterns of the lower limbs have been shown to reduce NCACL injuries among the high risk population, especially female athletes, given the reduction in biomechanical risk factors (Walden et al.,2012; Kiani et al., 2010; Mandelbaum et al., 2005; Myklebust et al., 2003; Hewett et al., 1999).

The disparity between positive laboratory results demonstrating NMT programs and the actual effects on injury outcomes among high-risk female athlete's population suggests a missing link between current published research and clinical applications of a prevention intervention programs (Michaelidis et al., 2014; Sugimoto et al., 2016; Myer et al., 2007). One proposed explanation for such a disparity between laboratory results and incidence outcomes may be related to the complexity and difficulty in implementing the techniques previously found to be successful in changing biomechanics and/or injury risk (Thompson et al., 2017; LaBella et al., 2011; Steffen et al., 2008; Gilchrist et al., 2008; Myer et al., 2005; Mandelbaum et al., 2005; Myklebust et al., 2003; Heidt et al., 2000; Hewett et al., 1996). Furthermore, some NMT programs used to decrease ACL injuries among female athletes often involve an entire team, requiring significant time commitments and may be perceived by athletes or coaches as a distraction from sport-specific skill training. Hence, such an arrangement could deter athletes and coaches from incorporating NMT into their pre-season or in-season conditioning programs (Steffen et al., 2008; Gilchrist et al., 2008; Mandelbaum et al., 2005; Myklebust et al., 2003; Soderman et al., 2000).

Most intervention programs have used comprehensive training strategies obtained from injury mechanism studies and different training aspects combining multiple components of balance, plyometric and strength training (Thompson et al., 2017; Steffen et al., 2013; Walden et al., 2012; Kiani et al., 2010; Ortiz et al., 2010; Steffen et al., 2008; Myer et al., 2005; Mandelbaum et al., 2005; Heidt et al., 2000; Hewett et al., 1996). Initial evidence indicates that those intervention programs were able to reduce some potential biomechanical risk factors for ACL injuries, particularly among high-risk female athletes (Letafatkar et al., 2015; Barendrecht et al., 2011; Cochrane et al., 2010; Lim et al., 2009; Myer et al.,2006; Hewett et al., 1996). However, it is still unclear whether the combination of multiple NMT components provided the prophylactic effect or whether it was a single component responsible for the observed neuromuscular and biomechanical adaptation resulting in the reduction in ACL injury risk and sustained rates among female athletes.

Several published works have evaluated the influence of a single aspect of NMT, investigating how each modality may affect ACL injury risk (Cochrane et al., 2010; Myer et al., 2006; Pfeiffer et al., 2006; Petersen et al., 2005; Myklebust et al., 2003; Soderman et al., 2000; Caraffa et al., 1996). Studies have shown that plyometric, strength and balance training may improve dynamic stabilization, which, in turn, would decrease the lower limb valgus motion and loads impulse, thus reducing impact forces during sport participation (Cochrane et al., 2010; Myer et al., 2005; Irmischer et al., 2004; Hewett et al., 1996). However, few studies to date have done this (Letafatkar et al., 2015; Herrington et al., 2010; Cochrane et al., 2010; Lim et al., 2009; Herman et al., 2008; Myer et al., 2006; Irmischer et al., 2004).

Plyometric or jump training has been included in many NMT programs (LaBella et al., 2011; Kiani et al., 2010; Gilchrist et al., 2008; Mandelbaum et al., 2005; Myer et al., 2005; Noyes et al., 2005; Myklebust et al., 2003; Hewett et al., 1999) and have been documented as decreasing ground reaction forces (GRF) during landing tasks and increasing hamstring strength (Irmisher et al., 2004; Hewett et al., 1996). In study by Herrington et al. (2011) reported that female athletes who participanted in 4 week jump based exercise program resulted in significant reduction in dynamic knee valgus post training. However, jump-based program exercises may subject the lower limb joints to rapid loads (Hewett et al., 2005), potentially exposing the athletes to demanding, high-intensity loads which may be overwhelming and also expose athletes to fatigue and injuries (Myer et al., 2007).

Moreover, although NMT programs that include strength training were among the most successful in reducing ACL injury incidence within the athlete population (Kiani et al., 2010; Mandelbaum et al., 2005; Hewett et al., 1999). However, strength training may not be considered essential for ACL prevention, as a number of prevention programs were effective in reducing risk and incidence of ACL injury without including strength training (Caraffa et al., 1996; Myklebust, et al., 2003; Myer, et al., 2006; Cochrance et al., 2010). The efficiency of a single-faceted strength training program regarding ACL injury prevention did not demonstrate promising results in reducing the risk of ACL injury (Cochrance et al., 2010; Herman et al., 2008).

Several studies have suggested that balance-training devices such as a wobble board or unstable surface can significantly improve knee and ankle muscle proprioception during rehabilitation (Waddington et al., 2004; Waddington et al., 2000; Wester et al., 1996). In addition, it can help prevent lower limb injuries (Fitzgerald et al., 2010; Nigg et al., 2006; Myer et al., 2006; Myklebust et al., 2003; Wedderkopp et al., 1999; Caraffa et al., 1996). Balance-training programs could be a supplemental training element to be implemented within knee and ACL injury prevention programs, due to the low to moderate intensity associated with the exercise. Interventions programs which incorporate proprioception and balance training utilise the principle that parts of the body act as a system of chained links, muscles and joints, whereby the whole limb is regarded as one kinetic functional unit, starting from the foot through the body segments (Haim et al., 2008; Zajec et al., 2002). However, balance training requires equipment which can be static and sometimes inconvenient to use, which was reflected by its low compliance rates (Andersson et al., 2013; Oslen et al., 2005; Myklebust et al., 2003; Soderman et al., 2000).

Recently, unstable footwear devices have been developed to mimic a stimulating effect on lower extremity neuromuscular control, similar to the wobble board, with the primary purpose of strengthening and improving activation patterns that may be relatively underutilised and inactive while wearing normal footwear (Farzadi et al., 2017; Plom et al., 2014; Landry et al, 2010). Several research works have indicated that the incorporation of unstable footwear may induce positive biomechanical effects (Farzadi et al., 2017; Price et al., 2013; Plom et al., 2014; Taube et al, 2008; Nigg et al., 2006; Waddington et al, 2004). Researchers have demonstrated an increase in lower limb muscle activity levels when using unstable footwear, which may justify the use of unstable footwear as a training method to improve lower limb muscle recruitment patterns and strength (Farzadi et al., 2017; Horsak et al., 2013; Demura et al., 2012). However, most unstable footwear has revealed several limitations. First, these cannot be adjusted, nor can the joint loads be manipulated on the lower limb, as they are restricted to the manufacturer's setup design. Secondly, they cannot be customised to an individual's needs. Finally, the majority demonstrated the ability only to increase instability in one motion plane, which is more to do with the nature of its design (Plom et al., 2014; Price et al., 2013).

Examining whether neuromuscular motor control learning can be transferred from laboratory conditions to the competitive field has raised the issue as to whether currently NMT programs used may not be sufficient to promote improvements in lower limb movements mechanics and muscular recruitment patterns to withstand high loads on the knee joint during risk sport movements (Benjaminse and Otten, 2011; Michaelidis et al., 2014; Sugimoto et al., 2015). Many prevention programs have been introduced to reduce ACL injury risk (Sugimoto et al., 2015; Stevenson et al., 2015). However, the majority require a time commitment and considerable level of complexity and intensity (Sugimoto et al., 2014, 2015). This appeared to deter athletes from participating and reduce their adherent rates to current NMT programs.

This brought up the need for a simpler yet effective intervention to be developed. Therefore, in this thesis the incorporation of a footwear biomechanics device such as the AposTherapy system into ACL injury prevention programs has been proposed. The rationale behind employing the AposTherapy system, which is a biomechanical foot-worn device using a platform in the form of a shoe, arises from the strong link between insufficient neuromuscular control and muscular coordination, and an increased risk of NCACL injury (Ford et al., 2003; Hewett et al., 2005; Myer et al., 2006). The AposTherapy system has previously been used in knee osteoarthritis patients and has shown the ability to reduce pain and improve the patient's functional measures (Haim et al., 2011; Bar-ziv et al., 2013). The AposTherapy system allows manipulation of the knee alignment resulting in reducing loads on the knee and at the same time introduces perturbation for motor learning (Haim et al., 2008, 2011; Goryachev et al., 2011).

The muscle recruitment pattern is essentially operated by the central nervous system, thus influencing the kinetic factors associated with NCACL injury (Yu and Garrett, 2007). The AposTherapy system is designed to enforce a biomechanical effect on neuromuscular control by its ability to simultaneously introduce perturbation through the creation of controlled micro-instability, which may challenge the dynamic stability of the lower limbs while modifying the chain of joints to its optimal alignment (Haim et al., 2010; Goryachev et al., 2011). The convex shape of the elements puts participants in a state of perturbation by having the participant walk with a device every day; the therapy is thereby considered to induce neuromuscular adaption towards the desired neuromuscular gait pattern (Bar-Ziv et al., 2013). This is exactly what is required from all NMT interventions if they are to enhance neuromuscular control in a bid to withstand the dynamic demand on the knee joint while performing high-risk manoeuvres. In addition, the unique application of the AposTherapy system can be used while engaging in daily activities (Bar-Ziv et al., 2010; Haim et al., 2010), either on its own or coupled with other components such as balance training in order to save time. thus, encouraging the use of intervention programs to address this serious injury. The flexibility of using the AposTherapy system can encourage its use as a more time efficient intervention component yet delivers the required neuromuscular control enhancement effect. As such, the AposTherapy system represents a promising addition to rehabilitation programs for post-ACL reconstruction.

Therefore, it was proposed that the AposTherapy system can be a useful tool in intervention programs for preventing ACL injury, particularly in individuals who have been identified as having an imbalance in neuromuscular control, thereby putting them at risk of injury. The primary aim of this thesis was to explore for the first time employment of the AposTherapy system to reduce knee valgus loads during single leg landing movements in high risk individuals (female recreational athletes and athletes who had previously sustained NCACL injury and had ACLR surgery). The hypothesis was that incorporating an unstable footwear device such as the AposTherapy system with other exercise elements, or alone, as part of a prevention program for reducing the knee valgus motion and loads, would achieve benefits in recreational female athletes who had shown a high risk of sustaining primary ACL injury. Additionally, the hypothesis was that such an intervention would also reduce the knee valgus motion and loads at the contralateral knee in athletes who had previously sustained NCACL injury and had ACLR surgery.

The thesis structure from this point forward starts with a literature review to demonstrate both the need and rationale for the work and present the overarching research question and hypotheses for the thesis. This is followed by chapter three which is a general methodology and repeatability study. The fourth chapter is a feasibility study on the AposTherapy system, as the device has not been utilised in cohorts of individuals with high 2D FPPA (>8.4°). Chapter five is a parallel RCT design trial whereby three groups of individuals were compared after an intervention period. In the sixth chapter the utility of the AposTherapy system was evaluated in individuals who have previously had an ACL reconstruction to determine whether the system can influence the contralateral knee. Finally, the discussion and future work brings the thesis to a close.

1.1 Thesis Structure.

CHAPTER 1

- Introduction
- Thesis structure

CHAPTER 2

- Background
- Literature Review
- Gap in literature
- Research question and hypothesis

CHAPTER 3

General Methodology and Reliability study

Reliability of using 2D analysis, 3D motion analysis, EMG, CoP –excursion, to measure biomechanics variables during SLS, SLL and Single Leg Stance tasks

CHAPTER 4

Feasibility study

The role of incorporating AposTherapy system on lower limb biomechanics in recreational female athletes with potential risk for non-contact ACL Injury-A feasibility study.

CHAPTER 5

Main study

The role of incorporating AposTherapy system on lower limb biomechanics in recreational female athletes with potential high risk for non-contact ACL injury- Pilot RCT study.

CHAPTER 6

Pilot study post ACL repair

The role of incorporating AposTherapy system on lower limb biomechanics in recreational athletes with a high risk for second non-contact ACL injury at contralateral limb, after primary ACL Reconstruction-Pilot study

CHAPTER 7

- Overall conclusions and Future work

Chapter two: Background and literature review.

Background

2.1 Anatomy and function of the Anterior cruciate ligament.

The anterior cruciate ligament (ACL) (Figure 2-1) is anatomically and functionally subdivided into two components, the smaller anteromedial bundle, and the larger posterolateral bundle (Dargel et al., 2007). The anteromedial fibres become taut as the knee is flexed and are the primary restraint against anteriotibial translation, with the posterolateral fibres tightening as the knee is extended. The latter tend to stabilise the joint near full extension, and particularly against rotatory loads (Petersen et al., 2007). Several research works have reported that the majority of the restraining force needed to prevent anterior tibial displacement at 30° and 90° of knee flexion comes from the ACL (Dargel et al., 2007).

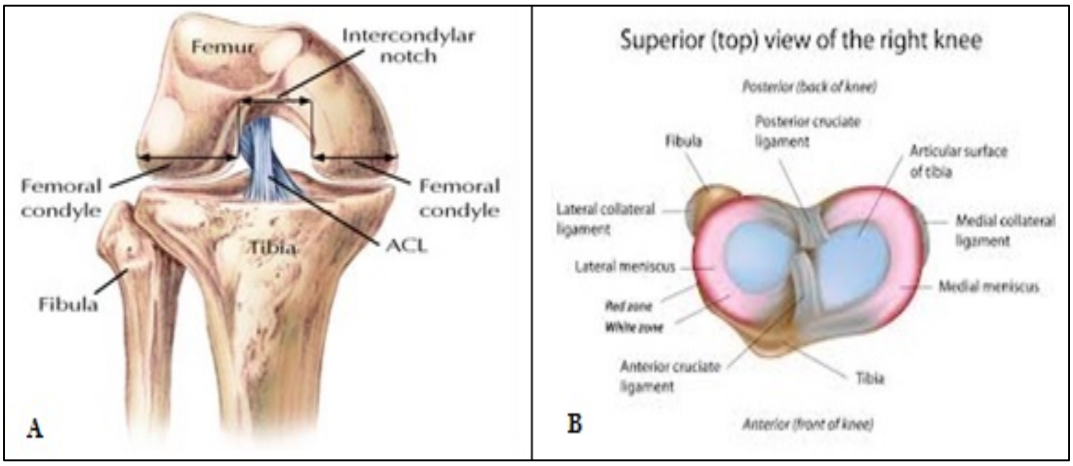


Figure 2- 1:Anatomy of the knee identifying the major ligaments. A. anterior view, B. superior view (www.precisionnutrition.com), (www.broadgatespinecentre.com).

It has been proposed that neurosensory information from the ACL would contribute to neuromuscular control of the lower limb and assist in providing dynamic knee stability which is important to withstand high loads on the knee joint during different dynamic tasks (Dargel et al., 2007). It has been suggested that any functional instability at the knee joint following ACL injury is due to a lack of coordination in muscle stabilisation of the knee joint, which is believed to be because of absent sensory feedback from the ACL to the neuromuscular system (Borsa et al., 1997).

The ACL is essential for insuring the dynamic stability of the knee and preventing hyperextension during jumping and/or landing, cutting and pivoting manoeuvres (Noyes et al., 2009). The ACL plays an important role in knee biomechanics. It is the primary restraint to anterior tibial translation through the arc of motion. In addition, it is also considered to be the secondary restraint to Varus/Valgus and internal/external rotation stress across the knee (Hewett et al., 2007).

2.2 Anterior cruciate ligament Injury.

The knee joint is considered one of the most commonly injured joints in sports. Knee injuries account for nearly 50% of all sports injuries (Olsen et al., 2003). An injury to the ACL is considered one of the most disabling severe knee injuries in sports (Lehmann et al., 2017). ACL injury has been documented to cause immediate disability for athletes which in many cases would also be followed with long-term consequences in terms of functional impairment in motor coordination (Hewett et al., 2016; Smith et al., 2012; Ageberg et al., 2004). It has been reported that the annual number of ACL injuries in the US was 200,000 which was based on an incidence rate of around 84 per 100,000 (Bates et al., 2015). Similarly, according to a study by Frobell et al. (2007), in Sweden, 81 ACL injuries occur per 100,000 individuals, whereas, according to a study by Webb and Corry (2000) reported that the annual number of ACL injury in the UK was 18,600, which was based on an incidence rate of around 30 in 100,000 individuals.

Although ACL injuries account for just 3% of all sport injuries in college sports, they account for around 88% of musculoskeletal injuries associated with 10 days or more of time lost from practicing sports (LaBella et al., 2014). ACL injuries may lead to significant residual restrictions on activity and mobility (Levine et al., 2013; Ajit et al., 2008) and result in significant short-, mid- and long-term morbidity consequences, with ACL risk exposure being 1 in 25,782 athlete exposures of an athlete’s participation (Uhorchak et al., 2003).

2.3 Consequences of an ACL injury.

ACL injuries result in a substantial negative impact on the health care system. The financial impact of ACL reconstruction (ACLR) is large. Cost utility analysis has found the financial cost for ACLR during a lifetime would cost the US society approximately $38,112 per person (Mather et al., 2013; Stevenson et al., 2015). The financial impact of ACL injuries would be worse were one to consider the additional cost of rehabilitation management, days off work, and potential loss of academic scholarships (Secrist et al., 2016; LaBella et al., 2014). The financial estimates for the management of ACLR from 1999 to 2000 was approximately \$17,000 to \$25,000 per ACLR (Hewett et al., 1999). However, it would be most likely that this cost has increased significantly during the last 16 years. It was estimated that just in the US, approximately 250,000 ACLR's are performed annually, with a financial impact of around \$2 billion annually (Secrist et al., 2016; Kiapour et al., 2014; Swenson et al., 2013).

In addition to those substantial economic costs and time lost associated with ACL injuries, various other negative consequences may result, such depression, low self-esteem, a feeling of social isolation, and mood disturbance, leading to lower academic performance (Sugimoto et al., 2012; Stevenson et al., 2015). This could mean endless negative effects on the individual and society (Mather et al., 2013). Nevertheless, the patient's academic performance could be greatly affected by an ACL injury. One study reported that 36% of the athletes in grades 6 to12, who sustained ACL injuries and required ACLR during the academic year underperformed and failed exams upon return to school, compared with 0% of those who had their ACLR done during summer breaks or holidays (Trentacosta et al., 2009). Additionally, the reduction in the ability to move could have a strong potential for increased weight gain, with all the associated health issues that result from high BMI, such as type 2 diabetes, cardiovascular diseases, CVA (cerebrovascular accidents), and fertility problems.

Athletes who sustain ACL injuries will suffer immediately from severe knee swelling with intense knee pain that is usually combined with knee instability (Renstrom et al., 2008; Mather et al., 2013; Stevenson et al., 2015). Noyes et al. (1983) followed up a population of ACL deficient (ACLD) participants and documented that around 31% of them complained of moderate to severe functional disability even during walking activities, while around 44% developed disabling symptoms during normal daily routine activities. The majority reported functional disability restricting them from participating in demanding sports requiring twisting and turning movements. Moreover, a recurrent episode of knee swelling was reported to happen four to five times in ACLD patients after an average of 11 years' follow-up (Noyes et al., 1983).

Reports have shown that 82% of ACL injured athletes managed to return to practicing the same level of sports after ACLR, which gives a false impression that the injury was not eventually disabling for sports (Li et al., 2017). In study by Brophy et al. (2012) they reported that more than 25% of football players who sustained ACL injury where not able to return to their previous athletic levels. Nevertheless, 65% of them no longer played after 7 years of their primary ACL injury. However, a significant number of these reinjure (31%) occurring in the first six months after returning to sports activities (Leys et al., 2012; Webster et al., 2016). This is more worrying when one takes into consideration that female athletes, when compared with male athletes who were sport and aged matched, were more likely to require ACLR and less likely to return to practicing their pre-injury sports after sustaining an ACL injury (Wiggins et al., 2016).

It has also been documented that individuals who sustain an ACL injury are at an increased risk of premature osteoarthritis, regardless of the applied management strategy (conservative or surgical) adopted (Zabala et al., 2015; Kaedling et al., 2015; Lohmander et al., 2007). Osteoarthritis has been documented to occur in athletes who have previously sustained ACL injuries, with a 10-fold higher risk of developing early onset degenerative knee joint osteoarthritis compared to individuals who did not sustain ACL injuries (Lohmander et al., 2004,2007). In studies investigating patients who sustained an ACL injury, they reported that 62% of them had developed radiographic osteoarthritis within 15 years of their ACL injury (Oiestad et al., 2010; Neuman et al., 2009). Therefore, the consequences of an ACL injury on the healthcare system and individual are numerous.

Lohmander et al. (2004) reported that 51% of female athletes with an average age of 19 years who sustained ACL rupture had shown evidence of radiographic knee osteoarthritic changes just twelve years post injury compared with only 7% of the uninjured contralateral knee, meaning that athletes would complain of osteoarthritic symptoms when they were in their early twenties and thirties, with all the issues associated with it, from restriction of movement and chronic knee pain with knee instability, which would disable the young population of athletes and cost society dearly (Zabala et al., 2015; Kaedling et al., 2015; Ajit et al., 2008).
Studies have documented that abnormalities in knee joint kinematics observed after ACL injury are likely to result in degenerative metabolic changes in regions of the cartilage tissue that were not able to adapt to the new load pattern (Lohmander et al., 2007; Andriacchi et al., 2006). The observed gait changes after ACL injury, cartilage accommodation to load, and the relationship between cartilage loads during motion and regional cartilage variations in biology and structure suggest that degenerative charges in cartilage after ACL injury could be related to gait changes that shift loads applied to cartilage. This alteration in loads may cause

regions of the cartilage to become newly loaded (Lohmander et al., 2007; Ajit et al., 2008). Being subjected to altered levels of tension and compression, or becoming unloaded with the metabolic sensitivity of chondrocytes to such alteration in the mechanical environment, combined with the low adaptation potential of mature cartilage, may result in premature degenerative changes (Lohmander et al., 2007; Ajit et al., 2008; Hewett et al., 2009). The relationship between the structural organization of healthy cartilage and the applied mechanical load suggest that knee joint cartilage regions are conditioned to their local mechanical environment (Lohmander et al., 2007; Ajit et al., 2008).

2.4 Mechanism of ACL injuries.

The ACL can be injured via a contact (impact) or a non-contact mechanism. The non-contact mechanism accounts for approximately 70% to 84% of ACL injuries (Boden et al., 2000; Olsen et al., 2004; Griffin et al., 2005; Fauno et al., 2006; Shimokochi et al., 2008; Hewett et al., 2009; Levine et al., 2013). Myklebust el al., (2003), defined NCACL injury (Figure 2-2) as an injury that occurs in the absence of any body-to-body contact. The majority of ACL injuries happen during single leg manoeuvers while landing from jump, deceleration or changing- direction during sports participation (Olsen et al., 2004; Boden et al., 2000; Myklebust et al., 1998). Furthermore, most NCACL injuries appear to occur close to foot strike, in knee-valgus and minimal-knee flexion positions (Boden et al., 2000; Olsen et al., 2004; Krosshang et al., 2007). The incidence of ACL injuries is relatively high in sports such as Basketball, Football, Handball, Volleyball, Rugby and Netball, which are characterised by frequent landing or rapid changes in direction while accelerating or decelerating (Myer et al., 2010; Hewett et al., 2006; Griffin et al., 2000). Myklebust et al. (1998), observed the mechanisms of ACL injury on a total of 115 ACL injuries in cohort of male and female athletes in both studies, and reported an incidence rate of 95% and 98% of the players reported that their injury happened in non-contact mechanisms.

Mathematic modelling studies demonstrate that perturbation to the lower limb when execution high risk athletic manoeuvres can result in external valgus loads that are capable of tearing the ACL and that the valgus loads occur more frequently in female athletes than their male counterpart (McLean et al., 2004). Bone bruises of the lateral femoral condyle or posterolateral portions of tibial plateau occur approximately 80% of the time in MRI (magnetic resonance imaging) studies after acute ACL injury (Viskontas et al., 2008; Quatman et al., 2009).

Previous studies that used video analysis to describe the mechanisms of NCACL injury seem to agree that in most cases, the NCACL injury occurred early after initial contact in landing or cutting manoeuvres with the knee in full extension (Boden et al., 2000; Teitz et al., 2001: Olsen et al., 2005; Griffin et al., 2006). Also, many situations resulted in a valgus collapse that is a situation in which the knee collapses medially from excessive valgus load (Krosshaug et al., 2007). Krosshaug et al. (2007), analysed the videos for 13 male and 17 female athletes to assess knee and hip motion during NCACL injury. The authors reported that the estimated time of injury ranged between 17 and 50 milliseconds after initial contact. No significant gender differences between female and male athletes were found at initial contact for knee valgus motion (4° vs 3°, p=0.7), but at 50/33 ms after initial contact female players had larger knee valgus (8° vs 4°, p=0.018) (Krosshaug et al., 2007). Interestingly, the mean hip adduction angles were consistent across gender and player's injury incidences ranged from 8 to 19 at initial contact as well as at 50/33 ms after initial contact (Krosshaug et al., 2007). The authors found that 72% of the ACL injuries did not involve contact with other players at the assumed time of ACL injury (Krosshaug et al., 2007).

This agreed with the outcomes by Boden et al. (2000) in which 72% NCACL injury were registered among 100 cases. Moreover, in a study by Arendt and Dick (1995) found 80% NCACL injury in female athletes and 65% in male athletes. Moreover, Koga et al. (2010), investigated knee joint kinematics in 10 ACL injury situations from female team handball and basketball players. The study described 3D knee joint kinematics in ACL injury situation using model-based image matching technique (MBIM). The authors documented that kinematic patterns were surprisingly consistent among the study cases. The mean knee valgus angle was in range (-2° to 3°) at initial contact, but had increased by (12°, 95%CI, 10°-13°) at 40 milliseconds at time of NCACL injury. Moreover, the mean peak vertical GRF was (3.2 BW, 95%CI, 2.7-3.7 BW) occurred at 40 milliseconds after initial contact. The study outcomes suggested that knee valgus loads are a main contributing factor in the NCACL injury mechanism. Therefore, NMT prevention programs focus on acquiring a good landing and cutting technique with high knee flexion and without high knee valgus loads (Koga et al., 2010).

Figure 2- 2:Mechanism of non-contact ACL injury (Krosshaug et al., 2007; Myer et al., 2010).

2.5 Risk factors for ACL injury.

A variable that is related to potential injury is defined as a risk factor (Zebis et al., 2016). Whittaker et al. (2017) highlight the significance of acknowledging that "injury is a concomitant of complex interaction of multiple risk factors and inciting events". Nonetheless, risk factors have been classified by Meeuwisse et al. (1994) as either extrinsic or intrinsic. Extrinsic risk factors are principally related to the type of sport activity while performing hazardous sports manoeuvres. Intrinsic risk factors are specific individual characteristics that may predispose an athlete to risk of sustaining an injury while performing hazardous sports manoeuvres. The combination of extrinsic and intrinsic risk factors may contribute to exposing individuals to be more susceptible to sustaining injury while performing athletic activities (Pfeifer et al., 2018; Zebis et al., 2016).

Smith et al. (2012) has also classified injury risk factors as either modifiable or non-modifiable. Modifiable risk factors could be altered by injury prevention/mitigation intervention programs, while the non-modifiable risk factors cannot be altered. For example, neuromuscular and biomechanical risk factors for non-contact ACL injuries in female athletes that are modifiable, neuromuscular training intervention programs have successfully been adopted to alter some of the biomechanical risk factor by influencing the neuromuscular risk factors (Monajati et al., 2016; LaBella et al., 2014; Myer et al., 2013; Smith et al., 2012).

Many studies have documented that the risk factors underlying NCACL injury risk are likely to be multifactorial in nature, where they propose several theories to explain this phenomenon (Lim et al., 2009; Hewett et al., 2006). These theories included intrinsic variables (hormonal, anatomic, neuromuscular, biomechanical movement pattern differences between gender) and extrinsic variables (shoe surface interactions, bracing, physical and visual perturbation) (Lim et al., 2009). The following will give a brief synopsis of the extrinsic and intrinsic risk factors associated with NCACL injuries with a specific focus on gender related differences.

2.5.1 Extrinsic risk factors.

2.5.1.1 Footwear and playing surface.

The interaction between the playing surface and athlete's footwear (Smith et al., 2012) has been highlighted as a risk factor for NCACL injury. A high level of friction between the shoe and the playing surface may be influenced by many factors, such as the type of playing surface, which could be grass or an artificial surface, the type of grass, or the floor type, the weather, and the design of the shoe (Colby et al., 1999; Boden et al., 2000). High torsional resistance at the interface between the playing surface and the sports shoe may enhance sports performance by improving athletic foot traction on the playing surface, but at the same time can have the potential to increase the risk for sustaining NCACL injuries (Olsen et al., 2003; Smith et al., 2012). Several studies have proposed that the shoe-surface interaction may influence the ACL injury incidence rate both in direct and indirect ways (Olsen et al., 2003; Smith et al., 2012). The direct effect would be through greater friction, which may transmit excessive loads to the knee during athletic activities such landing, pivoting and cutting manoeuvres. The indirect effect would be through alteration in neuromuscular recruitment patterns as the athlete adapts to differences in surface factors and shoes (Renstrom et al., 2008).

Due to the fact that ACL injuries in the majority of situations happen when the foot was planted and firmly fixed to the floor, it can be assumed that the friction between shoes and the floor surface was high (Olsen et al., 2004). In a study by Olsen et al. (2003), the study prospectively observed female handball players during their competition season and collected data on 53 ACL injuries. The outcomes indicated that the risk of ACL injury were higher on artificial floors (generally having higher friction) in comparison with wooden floors (generally having lower friction). Therefore, shoe and surface designs that result in a safer environment insuring a low shoe-surface traction as possible, yet should be able to provide sufficient friction to allow optimal performance (Olsen et al., 2003).

2.5.1.2 Competition and exposure time.

It has been demonstrated that athletes will be at greater risk of sustaining NCACL injury during competition than during practice (Myklebust et al., 2003). This outcome was consistent amongst most sports (Renstrom et al., 2008). The volume and frequency of exercise are determined by a busy schedule of competition and practice sessions, which may produce negative influences on knee's dynamic stability and increase the potential for sustaining ACL injuries (Luke et al., 2011). There have been concerns expressed regarding the increasing physical demands on athlete through overscheduling their seasons, which could contribute to overuse injuries (Luke et al., 2011).

2.5.1.3 Weather conditions.

Studies have demonstrated that weather conditions have an influence on the mechanical interface between the playing surface and foot (Olsen et al., 2004; Renstrom et al., 2008). Orchard et al. (1999), reported that the risk of sustaining NCACL injury was increased during the Australian football season during periods of low rainfall and high evaporation, which increases the proposition that weather conditions may have direct influence on the mechanical traction between the shoe and playing surface and this would have direct influence on potential of the athlete suffering from ACL injury. Nevertheless, meteorological conditions may affect the shoe surface interaction, which is most likely risk for sustaining NCACL injury (Olsen et al., 2003; Orchard et al., 2003). Meteorological conditions have been reported to be related to increase ACL injury, for example raining and wet conditions would decrease the friction between the shoe and playing surface, thus reduce the risk of sustaining NCACL injury (Smith et al., 2012; Volpi et al., 2016).

2.5.2 Intrinsic risk factors.

2.5.2.1 Anatomical risk factors.

Anatomical risk factors are difficult to correct. However, it is important to understand them to be able to identify these.

Static alignment.

Females have a relatively wider shaped pelvis, with a larger Q angle, that may be related to higher rates of ACL injuries within the female athletic population (Hewett et al., 2005). However, this cannot be considered as predictive of ACL injury risk in female athletes, as the dynamic injury mechanism is often not correlated with anatomical measures (Myer et al., 2005). In addition, they are by nature impossible to modify.

Anthropometric differences.

Several studies that investigated ACL injury risk factors have focused on anatomical measures, such as thigh length, tibia length, and body height (Ford et al., 2003; Hewett et al., 2005; Myer et al., 2005). Yet similar to static alignment, anatomical measures cannot be considered predictive for ACL injury, as dynamic measures are not often linked with anatomical measures (Hewett et al., 2005; Myer et al., 2005).

Femoral notch width.

Female have been reported to have a smaller femoral notch width relative to their ACL size when compared with male athletes (Keays et al., 2016; Hewett et al., 2006; Shelbourne et al., 1998) Studies have suggested that a smaller femoral notch width is correlated with a smaller ACL, which may result in a reduced strength to withstand loads on ACL (Keays et al., 2016; Hewett et al., 2006). However, this is also non-modifiable.

High BMI.

Unhorchak et al. (2003) observed 895 military cadets for four years and reported eight ACL injuries in the female athlete cadets while participating in athletic activities. These researchers concluded that a higher body mass, general joint laxity and a narrower femoral notch width were reported in the injured cadets compared to athletes with NCACL injuries. Other investigators have found female athletes who sustained NCACL injuries had a higher BMIs, wider hips, smaller joints, smaller ACLs, and high joint laxity (Soderman et al., 2000; Chandrashekar et al., 2006).

General joint laxity.

Hyperextension and general laxity were reported to significantly increase the ACL injury risk in female athletes (Hewett et al., 2006). Female athletes with general joint laxity were reported to demonstrate a 2.7 times higher risk of sustaining an ACL injury when compared with females with no general joint laxity (Unorchak et al., 2003). Studies have documented that general laxity not only affects the joint sagittal plane resistance, but also influences the coronal plane motion, which can increase strain on the ACL (Boden et al., 2000; Unhorchok et al., 2003; Hewett et al., 2005; Chandrashekar et al., 2006). Increased flexibility of the hamstring muscle has been proposed in some studies as a potential risk for ACL injuries when compared to matched controls (Hewett et al., 2006). No definitive evidence has been established between anatomical variables and ACL injuries (Smith et al., 2012; Volpi et al., 2016).

2.5.2.2 Hormonal and growth risk factors.

During the last two decades, several studies have proposed that fluctuations in sex hormone levels during certain periods of the menstrual cycle may have an influence on the material and mechanical properties of the ACL in female athletes (Renstrom et al., 2008). Several studies have documented that both relaxin and oestrogen are reported to influence the tensile mechanical properties of the ACL (Herzberg et al., 2017; Casey et al., 2014; Lefevre et al., 2013; Smith et al., 2012). As oestrogen receptors are located on human ACL fibroblasts, several fold increases in serum oestrogen concentrations during the menstrual cycle may reduce ACL strength. Thereby, it may be considered a possible contributor to NCACL injuries in female athletes who are training or competing during their menstrual cycle periods (Casey et al., 2014; Lefevre et al., 2013; Smith et al., 2012; Wojtys et al., 1998, 2002).

Studies have suggested that the acute fluctuations within hormone levels during the menstrual cycle may induce changes in the ACL’s metabolism that could weaken its strength and could potentially lead to increased vulnerability of the ACL and risk of sustaining an injury during athletic manoeuvres (Yu et al., 2001; Hewett et al., 2006). It has been proposed that oestrogen could directly and indirectly affect the female neuromuscular system, as decreased motor skills during the premenstrual phase been reported, which may indicate that oestrogen may have an effect on neuromuscular function (Smith et al., 2012). Oestrogen levels are known to have a direct effect on muscle, and may play a role in the dynamic muscle stability of the lower limb (Vescovi et al., 2011; Ruedl et al., 2009). Several studies have reported that NCACL injuries happen with higher frequency during the pre-ovulatory phases when compared with the later phases of the cycle. This effect may be due to variations in neuromuscular control and muscle contraction (Wojtys et al., 2000; Hewett et al., 2006).

However, there is conflicting evidence in the literature, as different studies have proposed that different phases of the menstrual cycle have the higher risk of NCACL injuries (Adachi et al., 2008; Ruedl et al., 2011). Some have cited the ovulatory phase (Wojtys et al., 2002; Adachi et al., 2008), whereas others cite the follicular phase (Wojtys et al., 2000; Myklebust et al., 2003). Moreover, there is a methodological challenge to providing precise observations of hormone levels and the required long-term monitoring with day-to-day measurements of the serum levels of sex hormones (Voskanian et al., 2013). Numerous studies with different designs for establishing menstrual cycle classification schemes and analysis techniques have been used to show that it is not possible to identify a valid phase of the menstrual cycle at the time of NCACL injuries during sporting activities (Wild et al., 2012; Smith et al., 2012).

During puberty, males will be exposed to a large surge of testosterone, which would have significant influences on increasing body strength and muscle mass (Hewett et al., 2006, 2009). This would allow the individual to better control his new body’s dimensions and changes to the centre of mass during sports manoeuvres (Hewett et al., 2006, 2009). In contrast, females experience only a limited rise in testosterone levels through puberty, resulting in a much smaller rise in muscle strength and mass that may be insufficient to control their new bodies dimensions and changes in mass centre during sport manoeuvres (Mather et al., 2013; Voskanian et al., 2013). Several studies have documented that female athletes have demonstrated an increased NCACL injury incidence as early as at the age of 12 to 14 years old (Myer et al., 2013; LaBella et al., 2014). During and after puberty, females experience a surge in sex hormones levels, which have been suggested to influence the risk for NCACL injuries in female athletes by indirect effects on neuromuscular development during puberty rather than through any direct effect on the mechanical properties of the ACL (Voskanian et al., 2013).

Biomechanical studies have proposed that during puberty the femur and tibia grow at a rapid rate during puberty in males and females (Voskanian et al., 2013). This rapid growth in the two longest levers in the human body would translate into greater torque on the knee joint (Hewett et al., 2004). The rise in body mass would translate into higher joint torques, which are more challenging to balance during high velocity sport movements (Hewett et al., 2004). Muscular strength and coordination increase with age and maturation in males, allowing them to cope with high dynamic demands on the lower extremities, as there would be sufficient motor control after puberty to support knee joint motion while executing athletic movements (Hewett et al., 2006). Male's and female's muscle strength and muscular recruitment patterns diverge during puberty (Hewett et al., 2004). Females in general demonstrate a reduction in neuromuscular adaptation post puberty (Hewett et al., 2004, 2005).

Male and female muscle flexibility patterns diverge during and after puberty. With maturation stages and chronological age, it appears the hamstring muscle levels of flexibility decrease in males, while hamstring muscle flexibility levels will increase in females (Hewett et al., 2006). High hamstring muscle flexibility has been proposed to be partially responsible for reduced knee dynamic control in female athletes and may result in placing high stress on the ACL (Hewett et al., 1996; Huston et al., 1996). One could conclude that the different development of hamstring flexibility between male and female athletes could be one of the factors for gender disparity in NCACL injury incidence during and after puberty. The decrease in hamstring activation levels could have the potential negative effect on the co-contraction between the hamstring and quadriceps muscles during landing and jumping manoeuvres (Ford et al., 2005; Myer et al., 2005).

2.5.2.3 Genetic factors.

Genetic background of the athlete has been recently considered to be a possible risk factor for sustaining an ACL injury (Smith et al., 2012; Hewett et al., 2016). Pruna et al. (2013), considered the role of genetic biomarkers in athletes sustaining non-contact muscle injuries, which showed the possibility and potential to consider the role of genetics in NCACL. In a RCT study by Walden et al. (2015) on 4556 young athletes age 12-17 years, reported a significant association between familial predisposition of ACL injury and ACL rupture. Moreover, in study by Ficek et al. (2013) on 91 professional male football players who had primary ACL injury versus 143 healthy football players, the authors documented that polymorphisms haplotype was associated with decrease risk for sustaining ACL injury in future. However, this is still an under-researched area and the understanding of the genetic influence on ACL mechanical properties is in early stages of research.

2.5.2.4 Neuromuscular risk factors.

Neuromuscular control, muscle coordination, and muscle recruitment patterns all have a direct influence on the dynamic loading of the ACL while performing athletic manoeuvres (Mclean et al., 2004; Hewett et al., 2010; Myer et al., 2013; Volpi et al., 2016). Poor neuromuscular control at the lower limb, especially at the knee joint, has been documented to predispose the female athlete to high risk of biomechanical movement patterns resulting in sustaining ACL injuries (Hewett et al., 2005; Paterno et al., 2010; LaBella et al., 2014). Neuromuscular control is defined as the unconscious efferent response to an afferent signal regarding dynamic joint stability (Mandelbaum et al., 2005). The afferent proprioceptive signals that elicit motor control can be distinguished by their roles, where the reactive motor control are a result of afferent input and are reflexive in nature. The time to elicit such muscle response is longer, thus it is thought to be more heavily involved with maintaining the posture control, whereas, feedforward motor control is the result of reactivation of lower limb muscles (Mandelbaum et al., 2005).

Abnormalities in neuromuscular control specifically in terms of muscular firing and recruitment patterns may be partially responsible for the sex disparity in NCACL injuries (Cowling et al., 2003; Zazulak et al., 2005). It is essential that an appropriate motor unit recruitment pool of a certain muscle, a synchronized recruitment of all muscle acting around the knee joint are required to achieve an optimal dynamic stability of the knee, and thereby protect the knee from high valgus loads (Kaeding et al., 2015). As previously mentioned most of the ACL injuries occurs in non-contact mechanism, and in contrast to contact injuries the risk of sustaining a NCACL injury appears to be related to neuromuscular control risk factors influencing the biomechanical motion and loading on the knee joint (Hewett et al., 2011; Myer et al., 2013), as these factors in turn affects the magnitude and timing of muscular activation and torque production that can serve to dynamically stabilize the knee during high risk sports movements (Hewett et al., 2005; Zebis et al., 2008,2009).

Three neuromuscular deficits related to biomechanical motion and loading during common athletic tasks include ligament dominance, quadriceps dominance and leg dominance (Hewett et al., 2004; Ford et al., 2003). The concept of ligament dominance was first introduced by Andrews and Axe (1985). Whereby, the lower limb musculature does not adequately absorb the forces when conducting high risk sport manoeuvres which result in excessive loading of the knee joint passive ligament structures especially the ACL, which supposed to resist anterior tibial translation and knee valgus loads (Ford et al., 2003). Another well documented neuromuscular deficit is an imbalance in muscle recruitment of knee flexors and extensors (Hewett et al., 1996; Ford et al., 2003). Female athletes have shown tendency to rely on their quadriceps over their hamstrings to produce dynamic knee stability while executing jump and landing sports activities (Hewett et al., 1996; Huston et al., 1996). In addition, the concept of leg dominance has been mentioned as another neuromuscular deficit were imbalance between muscle recruitment patterns and muscular strength of the opposite lower limbs, with one side often demonstrating greater dynamic control (Hewett et al., 1996; Ford et al., 2003).

The over reliance on one limb can put greater stress on that knee, whereas, the weaker side might not be able to effectively absorb the forces associated with sporting activities (Ford et al., 2003). This have been seen especially in female athletes who participated in high risk sports with pivoting and jump landing manoeuvres such as football and handball. In a study by Krosshaug et al. (2016) 700 elite female handball players were tested with 3D motion analysis and tracked for a period of 7 years. There were 42 NCACL injuries reported during the study observation period. Interestingly the non-dominant leg was injured in 26 (62%) players (Krosshaug et al.,2016). This could be related to leg dominance with lower muscular strength and recruitment patterns, thus the weaker limb may be compromised in its ability to withstand even average force and torques (Ford et al., 2003).

Any neuromuscular control deficit that limits the ability of the muscular recruitment pattern to work synergistically, within the passive joint restraints to maintain dynamic knee stability, may increase the risk for NCACL injury (Hewett et al., 2005; Myer et al., 2008). There is an increasing evidence in the literature suggesting that abnormal neuromuscular control of the lower limb biomechanics, in particular the knee joint during the performance of potential hazardous sporting maneuverers, is a primary contributor for ACL injury mechanics in female athletes (Hewett et al., 2005; Mclean et al., 2004; Hewett et al., 2002; Lloyd et al., 2001), specifically dynamic knee joint stabilization is achieved through a combination of active muscle torque and passive ligament restraint (Hewett et al., 2005).

In a study by Harty et al. (2011), it was suggested that female athletes with greater knee valgus alignment in static alignment would be more likely to exhibit greater knee valgus during sports movement tasks. If static alignment was highly related to frontal plane knee postural orientation during dynamic tasks, it would suggest that modification of dynamic knee valgus could be limited (Harty et al., 2011). Harty et al. (2011), evaluated the correlation of knee motion and moment measures of the lower limb of 37 female athletes using 3D motion analysis while performing Step down (SD), SLL and DVJ tasks. The authors reported no significant relationship between frontal knee plane angle in the static calibration trial and dynamic movement tasks. The lack of significant relationship between static and dynamic knee position has also been reported by Mclean et al. (2005), who evaluated 10 female and 10 male athletes, were the study at the correlation between three unilateral functional tasks which involve rapid directional changes; a side step, a side jump and a 180° cutting during shuttle run (Mclean et al., 2005). The study findings showed significant correlation in peak frontal plane angle across tasks (r=0.83). However, no significant relationship between dynamic knee valgus and static knee valgus measures was reported (Mclean et al., 2005). The absence of a correlation between static knee alignment and knee posture during dynamic activities would suggest that neuromuscular control factors are likely to influence knee alignment during dynamic activities and that they are amenable to NMT interventions (Mclean et al., 2005; Harty et al., 2011).

This alteration of normal neuromuscular control function around the knee joint is considered as one of the main factors for NCACL injury in female athletes (Hewett et al., 2016). For this specific reason, restoration of the neuromuscular control strategy would represent a fundamental element in any intervention program aimed at preventing NCACL injuries in female athletes (Kaeding et al., 2015). Efficient neuromuscular control is essential for maintaining dynamic stability of the joint by providing joint stiffness (Shultz et al., 2010). The neuromuscular control of the knee joint is established through a combination of proactive (preparatory), also known as feedforward, motor control and reactive, also known as feedback, motor control loops (Hewett et al., 2005). Dynamic knee stability is preserved by continuously adjusting the feedforward and feedback motor response (Palmieri-Smith et al., 2008). Preparatory motor control of musculature is developed during previously repeated motion patterns plus activating muscles around the joint prior to excessive loading conditions in order to absorb torques and to reduce stress on the passive joint restraint (Myer et al., 2005; Ford et al., 2003). Furthermore, preparatory motor control can actively stiffen the joint prior to unexpected perturbation and may be adjusted and learned through integration of previous movement training or experiences (Ford et al., 2011; Mandelbaum et al., 2005; Huston et al., 1994). Whereas, reactive motor control strategies rely on reactive loops alteration muscular recruitment pattern in response to situation that load the lower limb joints

(Ford et al., 2011). Thus the role of muscles and their interactions with movement will be considered next.

Antagonist-Agonist relationship.

Electromyography studies have reported that females have demonstrated a neuromuscular imbalance between the quadriceps (Q) and hamstring (H) muscle activation patterns (Palmieri-Smith et al., 2008, 2009). This is considered a significant gender-related muscle behaviour and is proposed to expose female athletes to higher risk of sustaining ACL injuries during sport activities (Sell et al., 2006; Myer et al., 2005).

Several studies have documented that female athletes performs different sport manoeuvres such as, cutting, pivoting and landing from a jump with less knee joint dynamic stability resulting from imbalance quadriceps and hamstrings co-contraction in compared with their male counterparts (Chappell et al., 2007; Huston et al., 2004; Pollard et al., 2004). These imbalances increase in loading on the knee joint would consequently increase ACL injury risk (Volpi et al., 2016; Hopper et al., 2017). In fact, quadriceps and hamstring co-contraction has been documented to decrease the frontal plane motion up to three-folds (Markolf et al., 1995). The diminished co-contraction between quadriceps and hamstring in female athletes contribute to greater knee joint dynamic stability (Palmieri-Smith, 2009; Lloyd et al., 2005).

Moreover, several studies have reported that female athletes showed a higher quadriceps muscular activation relative to the antagonistic hamstring musculature (Hewett et al., 2005; Malinzak et al., 2001; Hewett et al., 1996). This imbalance in muscular activation of the quadriceps would increase anterior shear forces during low knee flexion angles that happen during high risk pivoting and landing maneuverers (Myer et al., 2005; Markolf et al., 1995). Thereby, knee appropriate flexor muscular recruitment may prevent critical loads necessary to injured the ACL during high risk athletic maneuverers (Hewett et al., 2005).

Imbalance between medial-lateral knee muscles activation pattern.

A low medial to lateral quadriceps recruitment ratio combined with high lateral hamstring muscle activation would result in compression of the lateral side of the knee joint, opening the medial side of the knee joint and increasing the valgus torque on the knee joint, which will expose the ACL to high stress (Sell et al., 2006; Hewett et al., 2006; Myer et al., 2005).

A low knee joint compression during athletic movement may expose the passive knee restraint to dynamic valgus loads, which results in the medial femoral condylar lifting off the tibial plateau, which may increase the valgus loads on the ACL during deceleration from landing, pivoting, and cutting manoeuvres (Hewett et al., 2006; Ford et al., 2003; LIoyd et al., 2001). The muscle recruitment pattern of low medial hamstrings and quadriceps activation observed in female athletes reduces the ability of the active muscle control system to work synergistically with the knee joint's passive restraint to maintain dynamic knee stability (Myer et al., 2005; Rozzi et al., 1999). Achieving a balance between the medial and lateral hamstring and quadriceps muscle activations in female athletes may reduce the valgus loads on the knee joint and preserve the ACL during athletic activities (Palmieri-Smith et al., 2009).

Gender difference in Q-H muscular co-contraction levels have been observed in female's athletes, where higher levels of quadriceps muscle activation coupled with low levels of hamstring muscle activation, when compared to male athletes, and subsequently high levels of Q-H co-contraction are demonstrated (Myer et al., 2005). Moreover, female athletes have been reported to show imbalanced low medial to lateral quadriceps muscle activity (Myer et al., 2005; Hewett et al., 2010). Thereby, restoring balance between the medial and lateral thigh musculature in female athletes may decrease knee valgus angle which may result in reducing the loads on the ACL and potentially decrease the likelihood of an ACL injury (Andersson et al., 2013; Palmieri-Smith et al., 2008). Inadequate activation of medial thigh muscle which female athletes exhibit while performing cutting and landing manoeuvres may restrict their ability to counter extension and valgus loads, thereby, this promotes excessive knee extension and valgus loads and may place high loads on ACL (Letafatkar et al., 2015).

Studies have suggested there are two neuromuscular activation strategies that have been proposed to resist external loading at the knee joint during dynamic tasks (Palmieri-Smith et al., 2008, 2009). One strategy involves an indiscriminate co-contraction without selective based upon mechanical advantage. On the other hand, another strategy involves a selective activation of muscle with the mechanical ability to counter the applied valgus-varus loads. Both neuromuscular strategies had been shown to stabilize the knee joint in the frontal plane during isometric loads (Letafatkar et al., 2015; Palmieri-Smith et al., 2009). This lower ratio observed in female athletes was proposed to account for a significant proportion of the variance in the peak external knee valgus moment when compared with male counterparts

(Palmieri –Smith et al., 2009). Therefore, many research work focusing of risk mitigation for ACL injury in female athletes have suggested that those ACL injury prevention programs targeted the development and enhancement of motor programs which are characterized by coordinated muscle activity (Letafatkar et al., 2015; Hurd et al., 2006; Fitzgerald et al., 2000; Beard et al., 1994).

Altered muscle activity magnitude and timing pattern.

Several Electromyography studies have documented gender related differences in muscle activation magnitude and timing while performing athletic manoeuvres (Zazulak et al., 2005; Besier et al., 2003, 2001). Low hamstring activation with high activity contribute to increased ground reaction forces (GRF) and lower energy absorption associated with high ACL injury risks (Hewett et al., 2006). Female athletes demonstrated a preference for higher activation of the lateral hamstrings and quadriceps muscles while displaying low medial hamstrings and quadriceps muscular activities (Palmieri-Smith et al., 2008; Myer et al., 2005). Sufficient medial hamstrings and quadriceps muscular activities would promote resistance to valgus torque, which indicates that the neuromuscular strategy demonstrated by female athletes will be a potential risk for sustaining ACL injuries during sports activities (Palmieri-Smith et al., 2008). The ability to resist valgus loads may be negatively affected when females are performing sports activities. Inadequate muscle activations of the medial hamstrings and quadriceps would expose the ACL to high strain loads (Palmieri-Smith et al., 2009). Reduction in medical knee compression may negatively affect passive joint resistance by exposing them to high valgus loads, thus predisposing the female athletes knee joint to medial femoral condylar lift-off and increase the stress on the ACL (Hewett et al., 2005). Moreover, it has been documented that female athletes showed higher firing activation of their lateral hamstring during landing (Hewett et al., 2005; Rozzi et al., 1999). In addition, female athletes been reported to show decrease in medial to lateral quadriceps recruitment, which when combined with disproportional recruitment in medial hamstring muscle may negatively affect the control of frontal plane loads at the knee joint (Hewett et al., 2005; Myer et al., 2005; Ford et al., 2003).

Pre-activation of the proactive muscle group.

The lower limb muscles have been reported to be 40% to 80% activated at the time of initial contact while performing athletic landing movements (Besier et al., 2003, 2001). Biomechanical studies have shown that the high valgus alignment of the knee joint at initial contact is related to high pre-activation of the quadriceps muscle during landing movements (Ford et al., 2005; Hewett et al., 2004; Ford et al., 2003). Studies have also reported, after analysis of NCACL injuries, that the majority of them occur approximately 17 to 50ms after initial contact (Walden et al., 2015; Kubota et al., 2015; Koga et al., 2010; Krosshang et al., 2007; Myer et al., 2005). In a study by Zebis et al. (2009) who recruited 55 female athletes were screened prior to their competitive season. Five of the female athletes sustained NCACL injuries during the season, and there was a significant decrease in pre-landing muscle activity of the medial hamstring in female athletes who sustained NCACL injuries. The findings of this study have pointed out that specific muscle recruitment patterns may have a potential role in increasing ACL injury risk in female athletes during high risk athletic manoeuvres. Thus, the previous results may suggest that enhancing hamstring muscle activity may be relevant to ACL injury intervention programs (Zebis et al., 2009).

Poor Proprioception.

Proprioception of the knee through it's ACL mechanoreceptors have a major contribution in providing reflex protection of the knee joint against potential dangerous loads during sport activities (Zazulak et al., 2007; Lephart et al., 2002). The ACL is richly innervated and possesses specific mechanoreceptors (Hewett et al., 2006). Mechanoreceptors, including Pacinian corpuscles, Ruffini ending and Golgi tendon organ like receptors have been documented to be found in the human ACL (Mir et al., 2014). Detection of motion and joint position sense refers to proprioception (JPS) (Lephart et al., 2002). The JPS involves the orientation of joint position and is operated through several receptors known as mechanoreceptors (Panics et al., 2008). The ability of the ACL to sense elongation and torque propose that the ACL is vulnerable to these torques and translations (Voskanian et al., 2013; Hewett et al., 2006). The pattern of muscle co-activation of knee flexors and extensors in response to balance training that stimulate the ACL mechanoreceptors when exposing the knee joint to different plane torques could be modified by neuromuscular training (Hewett et al., 2006; Chmielewski et al., 2005).

Studies have documented that poor proprioception is considered to be a key risk factor for sustaining knee injuries, particular NCACL injuries (Hewett et al., 2006; Griffin et al., 2000). In study by Mir et al. (2014) they investigated JPS of the knee on a population of 30 young male athletes, where they compared JPS using electrogoniometer to assess knee joint angular displacement during normal weight baering situations and unstable single leg situations which mimic the high risk of NCACL loads. The authors reported that less accurate knee JPS during high risk positions was observed. In addition, core proprioception has been proposed as a potential risk factor for ACL injury (Hewett et al., 2011). It has been reported that female athletes who sustain ACL injuries demonstrate greater trunk displacement compared with uninjured athletes, and that trunk displacement may predict the ACL injury risk with 83% sensitivity and 75% specificity. However, due to limitations in the studies sample sizes, a definitive conclusion cannot be drawn (Hewett et al., 2011).

Postural stability.

Postural control is defined as the ability to oversee body alignment and position in space. This will involve a multimodal interaction between neural and musculoskeletal systems (Shumway-Cook et al., 2012). Postural control consists of two components postural stability and postural orientation (Lehmann et al., 2017). Postural stability to a large extent assimilates somatosensory information to control the centre of mass (COM) in relationship to the base of support (Shumway-Cook et al., 2012). The deviation of COM away from the BOS during dynamic athletic activities has been recognized by several authors as a mechanism of increasing knee valgus loads on ACL (Hewett et al., 2009; Krosshaug et al., 2007).

While, postural orientation demonstrates vestibular and visual information to the central nervous system monitoring the interrelationship between environment relative to body segment (Baumeister et al., 2011; Shumway-Cook et al., 2012; Nae et al., 2017). Postural orientation, defined as the ability to stabilize body segment in relation to each other and to the environment during a static or dynamic tasks (Nae et al., 2017). Postural orientation reflects by kinematic outcome that can be measured by clinical observation or motion-analysis technology such as two-dimensional (2D) and/or three-dimensional (3D) motion analysis techniques. The knee joint position, in particular knee valgus motion is commonly assessed as a measure of postural orientation, for example knee valgus motion (Nae et al., 2017). Research work indicate that patients with ACL injury had an increased knee valgus angle measured with 3D motion analysis, compared with healthy controls (Nae et al., 2017; Goerger et al., 2015; Yamazaki et al., 2010; Hewett et al., 2005).

Studies have demonstrated that balance training shows the ability to improve postural control, which is considered a desirable adaptation when recovering from injury during rehabilitation or event in case for injury prevention purposes (Farzadi et al., 2017; Lahmann et al., 2017; Dingenen et al., 2016; Plom et al., 2014; Zech et al., 2010; Landry et al, 2010; Myer et al., 2006; Myklebust et al., 2003). Proprioception of the knee through its ACL mechanoreceptors have major contributions in providing reflex protection of the knee joints against potential high loads during sports activities (Lephart et al., 2002; Shumway-Cook et al., 2012). Several studies documented that poor proprioception is to be considered a key risk factor for sustaining knee injuries, particular NCACL injuries (Hewett et al., 2006; Griffin et al., 2006).

Studies have postulated that balance training induced changes in the muscle activity were to a large extent related to neural adaptation instead than to alteration in muscle properties (Zech et al., 2010; Gruber et al., 2007). Balance training have been suggested to change feedback of mechanoreceptors which may lead to sensorimotor integration and subsequently to adaptation of neuromuscular control reflected in alteration in muscle recruitment pattern (Zech et al., 2010; Gruber et al., 2007). This may explain the persistence of functional impairment such as deficit in postural stability, prolonged muscular reaction time and reduction in muscular magnitude as result to ACL rupture (Wojts et al., 2000; Henriksson et al., 2001). Therefore, it is logical to assume functional improvements such as postural stability and reduction in the risk of sustaining ACL injury after neuromuscular training may be associated with adaptation in motor response (Wikstrom et al., 2009; Emery et al., 2005; Hewett et al., 2002).

It been documented the use of CoP measures to be considered a useful tool to evaluate postural stability (Lehmann et al., 2017) and are a helpful procedure for physicians and physiotherapist to identify individuals with potential risk for sustaining ACL injury (Lehmann et al., 2017). The centre of pressure (CoP) trajectories is the vector of total force applied to centre of the support surface (Winter et al., 1990). A shift of CoP trajectory magnitude is an indirect measure of postural stability, as it is a measure of an individual's ability to maintain balance (Shaulian et al., 2018; Farzadi et al., 2017). Postural stability in the anterior-posterior (A/P) direction and medial and lateral(M/L) direction are the result of the small contraction of lower limb muscles to maintain an upright position (Farzadi et al., 2017). The area of sway which represent the total area of covered by CoP in both (A/P) and (M/L) direction was expressed as CoP excursion (Lehmann et al., 2017).

Several studies have investigated proprioception and balance training to maintaining upright posture and enhance posture control under dynamic conditions (Paterno et al., 2004; Nigg et al., 2006). Balance and proprioception training has been defined as exercise designed to focus on equilibrium maintenance and posture awareness without alteration of the base of support (Paterno et al., 2004; Risberg et al., 2001). Therefore, it has been incorporated in a variety of injury prevention programs (Caraffa et al., 1996; Mylkelbust et al., 2003; Olsen et al., 2005; Paterno et al., 2004; Myer et al., 2005,2006; Chappell &Limpivsasti, 2008; Kato et al., 2008; Cochrane et al., 2010; Kiani et al., 2010; Nagano et al, 2011; Barendrecht et al., 2011; LaBella et al., 2011; Lindblom et al., 2012; Walden et al., 2012; Letafatkar et al., 2015). Furthermore, several studies have suggested that the key principle underlying the perturbation was to expose a carefully controlled torque that destabilises the knee joint enough to generate appropriate responses without exposing the knee joint to any further risk (Anderssion et al., 2013; Letafatkar et al., 2015).

In a systematic review by Negahban et al. (2014) documented that postural control contributes to ACL mechanical proprieties though sensorimotor control by maintaining proprioceptive function. A shift of centre of pressure trajectories (CoP-Excursion) is an indirect measures of postural stability. Thereby, would be considered as a measure of an individual's ability to maintain balance (Farzadi et al. 2017). Furthermore, studies document increases in anterior-posterior and medial-lateral (A/P and M/L) direction may reflect postural stability impairment along these two axes (Lee et al., 2015; Rougier et al., 2012; Palmieri et al., 2002; Lysholm et al., 1998). Nonetheless, postural stability in the A/P and in the M/L direction was the result of small contraction of lower limb muscle to maintain an upright position (Farzadi et al. 2017).

In a study by Paterno et al. (2004) which demonstrated that six weeks of NMT, which included balance functional exercise, resulted in improvement in anterior/posterior (A/P) postural stability magnitude in young female athletes. However, the study outcomes showed no significant improvement in medial/lateral (M/L) magnitude. The authors postulated that this may be attributed to one direction (A/P) perturbation on unstable surface being utilised. Hence, the training program failed to sufficiently stimulate postural stability improvement in the (M/L) magnitude (Paterno et al., 2004). The proposed function-balance training program was to enhance lower limb dynamic stability and muscular coordination to properly control torque and maintain balance and upright posture, which would subsequently help to regenerate the required torque in the desired directions (Paterno et al., 2004). The authors suggested that female athletes who participated in the study would benefit from better levels of dynamic knee stability as a result of improvements in their postural stability. Hence, it may reflect in reducing the risk of ACL injury.

However, the study did not report ACL injury incidence among participants. Hence, no conclusion could be obtained. Furthermore, A study by Heitkamp et al. (2001) investigating the effect of implementing short-term balance training on equal mixed study sample of physical active adult females and males who participated in balance training intervention program for 6 weeks twice week for 25 min session and compared it with equal match control group who were performing strength training for similar period. The authors reported that there was improvement in balance measures during single leg stance test more in the balance training intervention group. Nevertheless, there was similar improvement in muscle strength of the knee flexor and extensor in both study groups (Heitkamp et al., 2001).

2.5.2.5 Leg Dominance.

Differences in the dynamic demands between the supportive and dominant limb during sport activities would affect intrinsic properties such as movement pattern, balance, and strength and therefore could be considered a risk factor for ACL injury (Negret et al., 2007; Faude et al., 2006; Matava et al., 2002). Gabbard and Iteva (1996) documented that the right side was the dominate lower limb in 75% to 82% of the general population. It been reported that the dominant leg had better proprioception, superior strength and greater knee flexion range of motion than the non-dominant supporting limb (Ross et al., 2004).

The dominant leg has been defined to be the leg that athletes would prefer for kicking a ball for a maximum distance (Ford et al., 2003; Hewett et al.,2005; Zazulak et al., 2005; Palmieri-Smith et al., 2008,2009; Mizner et al., 2012; Nilstad et al., 2014; Dawson et al., 2015; Letafatkar et al., 2015; Krosshaug et al., 2016). Studies have found that the dominant leg showed the predominance of ligament injuries of the knee and ankle joints (Svensson et al., 2018; Nilstad et al., 2014). However, when looking at studies that focus on the incidence of NCACL injuries alone they reported that female athletes who sustain NCACL injuries have them occur more in the support leg, which would be the non-dominant side (Krosshaug et al.,2016; Ruedl et al., 2011; Brophy et al., 2010; Negrete et al., 2007; Johnson et al.,2006).

In a study by Krosshaug et al. (2016) 700 elite female handball players tested with 3D motion analysis and tracked for period of 7 years. There were 42 NCACL injuries reported during the study observation period. Interestingly the non-dominant leg was injured in 26 (62%) players (Krosshaug et al.,2016). This could be related to leg dominance with lower muscular strength and recruitment patterns, thus the weaker limb may be compromised in its ability to withstand even average force and torques (Ford et al., 2003). Moreover, Brophy et al. (2010) reported that male athletes had a significant number of ACL injuries occurring in their preferred kicking leg, while female athletes showed a higher trend to injure the ACL on their preferred support leg. The study results showed that around 68% of female athletes sustained NCACL to the left knee (non-dominant leg), while only 26% of male athletes injured their left ACL during sports activities (Brophy et al., 2010).

Furthermore, Negrete et al. (2007) analysed the relationship between the side of injury, gender, and leg dominance in 302 patients with NCACL injury. There was a strong trend for female athletes to sustain more NCACL injuries to their left side (supportive leg) than to their right side (dominance leg). The authors reported that 96% of males and 99% of females studied preferred their right leg for kicking. Interestingly, when looking at NCACL injuries separately. Similer finding were reported in a study on recreational skiers who sustained NCACL injuries during practice and competition (Ruedl et al.,2011) reported that female athletes demonstrated a two-fold higher risk of sustaining NCACL on their non-dominant leg. Moreover, Johnson et al. (2006) reported that female skiers had a 2.4 times greater ACL injury risk than males, and that ACL injuries happened 85% more frequently to the left knee joint. The right side was reported to be the preferred kicking leg for male and female athletes enrolled in the study. Therefore, it has been suggested that if the non-dominant leg acts as the supported limb and if there is low motor control in the non-dominant leg, that leg may show high knee valgus loads, and therefore have a higher risk of sustaining ACL injury.

2.5.3 Biomechanical risk factors.

2.5.3.1 Frontal plane loads.

Computer modelling experiments have demonstrated a link between the NCACL injury mechanism and high dynamic knee valgus (Fukuda et al., 2003; LIoyd et al., 2001). The term dynamic knee valgus is not limited to knee joint motion, rather, it entails a combination of motion at all three joints of the lower limb, including hip internal rotation, hip adduction, knee abduction, tibial rotation, and ankle eversion (Hewett et al., 2006). Several studies have linked knee valgus loading resultant increase in stress on ACL this has been demonstrated experimentally through both in vivo and cadaveric research work (Hewett et al., 2005; Fukuda et al., 2003; Lloyd et al., 2001; Kanamori et al., 2000; Markolf et al., 1995).

Video footage of injury situations represents objective sources of information on the knee valgus motion involved in the injury mechanism (Olsen et al., 2005; Krosshaug et al., 2007; koga et al., 2010). Several studies have observed high knee valgus motion and moments in the frontal plane while performing jump landing manoeuvres (Ford et al., 2003,2005; Mclean et al., 2004,2005). These observations have led to postulate that frontal plane biomechanics are important to consider as separate and significant risk factors for NCACL injury, especially female athletes (Hewett et al., 2005; Quatman et al., 2009), and ACLR individuals who previously sustained primary ACL injury (Paterno et al., 2010). The growing body of evidence supporting knee valgus motion and moments as a risk factor for ACL injury, will motivates the need to identify high risk individuals with potentially dangerous movement pattern (Mizner et al., 2012).

In a prospective study of 205 healthy female high school athletes by Hewett et al. (2005) the injured female participants demonstrated 8° greater knee valgus angles than the uninjured female athletes off the control group had during landing ($p=0.01$). The female athletes who went on to sustained NCACL injury had a 2.5 times greater knee valgus moment moment (45 ± 28.5Nm/kg) when compared to the uninjured female athletes (18.4 ± 15.6 Nm/kg, $p=0.01$). Additionally, the vertical GRF was 20% higher in the injured cohort. The author reported a significant correlation existed between peak GRF and knee valgus angle and moment in female athletes who went to sustained NCACL injury (Hewett et al., 2005). The study reported the knee valgus (abduction) moment (Figure 2-3) to be a strong predictor for future NCACL injuries, with 78% sensitivity and 73% specificity (Hewett et al., 2005).

However, a recent report by Norcross et al., (2017) does raise caution with this finding as Hewett et al., (2005) used non-normalised moments and when normalised moments were used, no significant difference was found.

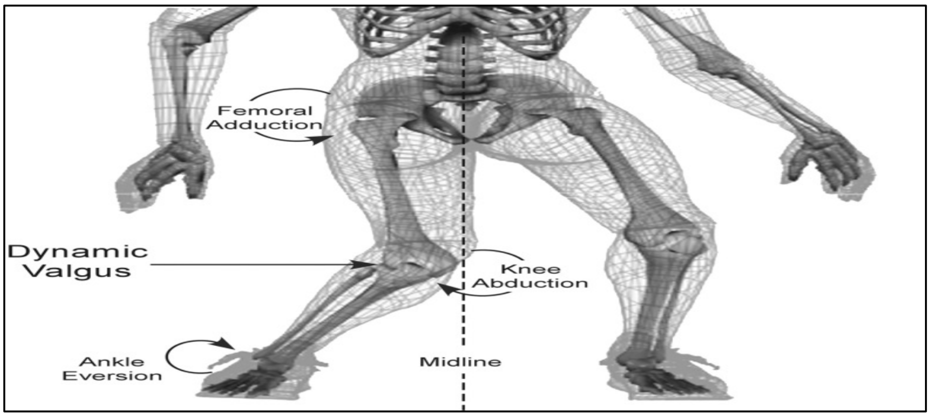


Figure 2- 3:Illustration of the biomechanical risk factors for non-contact ACL injuries (Hewett et al.,2005).

A systemic review by Sharir et al. (2016), reported that many studies considered female athletes with increased frontal plane knee valgus motion and moment with high potential risk to sustaining ACL injury when compared with age and skill match female athletes with normal values. However, this was built on the observation reported by Hewett et al. (2005) which was observed in a small sample (female adolescent 15-16-year-old athletes) of injuries in his study. Thus, the finding of the study by Hewett et al. (2005), by considering high knee valgus motion and loads as the major risk factor for ACL injury in female’s athletes, which could be considered as parameter bias. Therefore, this could make the results of many studies on ACL injury prevention or risk questionable (Sharir et al., 2016). Krosshaug et al. (2016), collected prospectively 3D motion analysis data while performing DVJ task from 700 Norwegian professional handball and football athletes. The authors reported 42 NCACL injuries and registered increase medial knee position reflect high knee valgus motion. Medial knee positioning was the only factor associated with increased risk for NCACL. However, receiver operating characteristic curve analysis indicated a poor combined sensitivity and specificity when medial knee position was used as a screening test for predicting ACL injury (Krosshaug et al., 2016).

The screening task DVJ has been used widely to assess athlete’s movement patterns to identify those who are at higher risk of ACL injury (Herrington et al., 2017). Those at greater risk of sustaining ACL injury might appear to have higher knee valgus loads (Hewett et al., 2005; Myer et al., 2010). However, the nature of functional tasks makes it difficult to discriminate between two lower limbs as it is a bilateral task, whereas, most ACL injuries occurs during single limb activities (Faude et al., 2006). Thus, single leg landing task may be relevant for assessment as a unilateral functional task (Herrington et al., 2017). Hip adduction and knee valgus have been observed to be greater when the individual undertakes unilateral tasks in compare to bilateral tasks (Pappas et al., 2007). Furthermore, in a study by Munro et al. (2012), the author reported that dynamic knee valgus might be more readily identified by SLL functional tasks compared with DVJ tasks because the SLL tasks is more likely to create a greater requirement for braking forces during landing.

Nevertheless, The DVJ task is frequently chosen as it replicates the task from the prospective evidence (Hewett et al., 2005). It has the advantage that it is simple and reliable, however, its credibility as an ACL injury manoeuver has been questioned (Kristianslund and Krosshaug, 2013). Moreover, the DVJ task does not replicate sport-specific landings, which are commonly only executed on one leg (Kristianslund and Krosshaug, 2013; Morgan et al., 2014; Sharir et al., 2016). Kristianslund and Krosshaug. (2013), reported 5-time higher peak knee valgus moments in a handball female players during the performing of cutting manoeuvre compared with DVJ task. Furthermore, there was no association between both functional tasks. The authors concluded that DVJ task cannot re-produce similar loading patterns of motion when ACL injury are known to occur. The single leg functional tasks such single leg landing (SLL), would expose the individual to greater loads to the lower limbs when compared with bilateral functional tasks such as DVJ with the largest amount of GRF higher knee loads (Harty et al., 2011). This was obviously when comparing the GRF observed when performing DVJ task from a higher height than the SLL, the GRF values demonstrated were considerably less (DVJ=1.8 BW vs SLL=3.4 BW), as during DVJ the athletes would shares the impact of landing with both legs (Harty et al., 2011).

In addition, the gender-related difference that is observed in the incidence of NCACL injuries is strongly influenced by a disparity in the coronal plane joint loads and motions (Hewett et al., 2006). Increased hip adduction moments during landing tasks may indicate that female athletes have difficulty controlling their hips, which may increase the knee dynamic valgus and increase the risk of ACL injury (Ford et al., 2003). Asymmetry of hip adduction muscle activation combined with dynamic coupling between the lower limb segments of the kinetic chain may predispose the lower limb to high valgus positions during landing manoeuvres (Ford et al., 2003; Lloyd et al., 2001).

2.5.3.2 Sagittal plane loads.

Female athletes have been reported to have high knee extensor activation and low knee flexor, which would increase the knee valgus alignment at initial contact during cutting and landing sports manoeuvres (Myer et al., 2005; Hewett et al., 2004). However, sagittal plane variables such as the hip and knee flexion-extension moments were not considered to be significant predictor for risk of sustaining NCACL injury (Mclean et al., 2005). This observation is with agreement with previous studies which multiple regression analysis incorporating flexion and extension moment, flexion angle and valgus torques forces at the knee joint were the sole significant predictor of peak landing forces (Hewett et al., 1996). Leppanen et al. (2017) conducted a prospective study on 171 young female basketball and floorball athletes. The authors used 3-dimentional motion analysis while performing DVJ task. 15 NCACL injuires were reported among the study participants after follow-up period of 1-3 years. The authors documented stiff landing with low knee flexion was associated with NCACL injuried athletes. However, the receiver operating characteristic curve analysis revealed that low knee flexion could not be used for prediction for ACL injury (Leppanen et al., 2017). This founding was similer with once reported by Hewett et al. (2005) in prospective study which demonstrated no differences in sagittal knee moments were observed between the injured and uninjured athletes, although the hip flexion moment was higher in female's athletes who sustain ACL injuries compared with uninjured athletes (Hewett et al., 2005). When looking from a kinematic perspective, the peak knee flexion angle at landing was 10.5° higher in the uninjured group who showed knee flexion angle of (82.4°±8.0°) compared with (71.9°±12.0°) at the injured athletes. Female athletes have been shown preference to land with a lower knee flexion angle at initial ground contact when compared with male athletes (Renstrom et al., 2008). Female athletes mainly absorb the force of impact using their knee and ankle joints, while male athletes would rather land with higher knee flexion angles and less planter flexion on initial contact, which would allow the landing impact to be absorbed mostly by the large muscles such as the hip abductors (Decker et al., 2003; Renstrom et al., 2008).

Several studies have found that knee flexion between 0º and 30° may increase the stress on ACL (Beynnon et al., 1995,2004). Beynnon et al. (1995), have report that contraction of the quadriceps increases ACL strain between 15°and 30°of knee flexion. Infect, both studies documented that the highest strain is might occurring at 15° knee flexion, which corresponds closely with the estimated knee positon at the time of ACL injury (Olsen et al., 2004). The relationship between the knee flexion angle and the potential for ACL injury has also been explored extensively in the literature interview and video studies indicate that ACL injury usually occurs at low knee flexion angles (0-30°) (Krosshaug et al., 2007; Quatman et al., 2009). Cadaveric studies show that the knee joint have potential to translate more in the sagittal plane during low knee flexion angles, and anterior tibial shear forces may generate loads on the ACL during 20-40° of knee flexion angles (Markolf et al., 1995). In addition, electromyography studies documented that female have considerable neuromuscular imbalances between knee extensors and flexors recruitment, which create difficulty for deceleration from a landing and control of anterior tibial translation contraction (Quatman et al., 2009). Cadaveric and mathematical modelling studies indicate that muscular co-contraction of hamstring and quadriceps can lead to joint compression and effectively reduce excessive loads in the ACL, particularly between knee flexion angle exceeding 60° (Quatman et al., 2009).

The knee extensors (quadriceps) contractions have been documented to cause a large anterior shear forces at angles close to full extension (Pandy et al., 1997). This postural orientation was observed during ACL injury incidences (Koga et al., 2010). Furthermore, knee extensors effects to cause anterior tibial shear decreases as knee flexion angle increase, due to the change in force line (Hashemi et al., 2011; Herrington et al., 2017). On the other hand, contraction of the knee flexors (hamstrings) may help to reduce the anterior shear force, which may prevent ACL injury (Li et al., 1999). Nonetheless, the distribution of landing forces on the hip and ankle will help to reduce the loads on ACL. Therefore, the anterior tibial shear alone is unlikely to cause ACL injury (Chandrasheker et al., 2006).

Several studies have highlight the link between ACL injury risk and small knee flexion angles (Li et al., 1999; Pandy et al., 1997). The knee flexion angles during landing from different tasks was found to be 5-10° less in female than male athletes (Huston et al., 2001; Malinzak et al., 2001). However, in study by Hewett et al. (2009), reported no significant differences in knee flexion angle between females and males ACL injured subjects or between female ACL injured subjects and their age and skill matched female's controls. Therefore, it is less likely for knee flexion angle to be the potential risk for higher rates of ACL injuries in females when compared to their male athlete's counterparts. The literature on ACL injury risk factors presume that forces caused by sagittal plane mechanisms may have been over estimated with regards to their potential to cause ACL injury (Munro et al., 2012; Mclean et al., 2005,2004). Mclean et al., 2004, reported that biomechanical modelling has suggested that frontal plane loading is more important in knee injury. Thereby, frontal plane loads and motions would be the best plane to investigate for knee injury risk in particular ACL injury risk.

2.5.4 Previous ACL injury.

Athletes who have previously sustained a ACL injuries and have had ACLR surgery showed a higher risk of sustaining a second ACL injury (either graft failure or a contralateral injury) compared with individuals who did not sustain primary ACL injuries (McCullough et al., 2012; Paterno et al., 2012, 2015). They could be due to a combination of incomplete injury rehabilitation or a rushed return to sports (Allen et al., 2016; Wiggins et al., 2016). In a systemic review of 5-year follow-up outcomes after ACLR, Wright et al. (2011), reported a 17.2% second ACL injury rate, with a greater percentage sustaining a contralateral ACL injury (11.8%) and (5.4%) at the ipsilateral graft failure. In a systematic review, Wiggins et al. (2016) demonstrated that one of every four athletes who had previously sustained an ACL injury and who then return to same high level of sports had high risk of sustaining another ACL injury during the period of returning to play.

A retrospective study of female soccer players reported that 28% of the players suffered a second ACL injury, with 11% of them rupturing their grafts, and 17% sustaining ACL injuries in the contralateral knee (Allen et al., 2016). The overall potential risk of sustaining second ACL injury following a primary ACLR within the first year was documented to be 15 times greater than healthy young athletes with no medical history of ACL injury (Paterno et al., 2012). Furthermore, Paterno et al. (2014), in study with follow-up for period of 2 years on a group of 78 athletes (age 17.3±3.1 years) who had ACLR and another group of age and skilled matched athletes with no history of ACL injury. The authors reported an overall second ACL injury rate of 29.5% within 2 years of return to sports after ACLR. There was 20.5% of the second ACL injuries at the contralateral knee and 9% accorded at ipsilateral graft. In addition, there was a trend toward a higher proportion of female participants 23.7% who suffered a contralateral injury compared with 10.5% with male participants. In contrast, for ipsilateral graft ruptures the incidence proportion between female participants 8.5% and 10.5% in male participants (Paterno et al., 2014).

ACLR surgery continues to be the standard management procedure for symptomatic ACL-deficient athletes who aim to return to high-level sporting activities (Hewett et al., 2013; Paterno et al., 2014; Hart et al., 2016; Nagelli et al., 2017). However, outcomes are widely varied (Gobbi et al., 2006; Busfield et al., 2009; Hartigan et al., 2010; Dunn et al., 2010; Raines et al., 2017). Furthermore, the current surgical intervention for an ACL injury may adequately address the patho-anatomy. However, underlying neuromuscular and biomechanical preoperative risk factors may persist after ACLR (Paterno et al., 2010; Melick et al., 2016). Nonetheless, rehabilitation after ACLR mostly focuses on post-operative impairments of the involved limb and may neglect to address modifiable risk factors in both limbs in those athletes after ACLR (Hewett et al., 2013; Paterno et al., 2015; Paschos et al., 2017). Paterno et al. (2010), conducted cohort study were 56 young male and female athletes underwent a prospective biomechanical screening after ACLR using 3D motion analysis while performing DVJ task and postural stability assessment before the study participants returned to sports activities. The authors reported that 23% (13/56) of the participants suffered a subsequent second ACL injury. The study documented that sagittal plane knee moments at landing, frontal plane knee kinematics, transvers plane hip kinetic, and deficits in postural stability might predicted a second ACL injury in this high risk population with sensitivity (0.92) and specificity (0.88) (Paterno et al., 2010).

Post-ACLR rehabilitation protocols have evolved greatly over the past few decades, shifting from conservative efforts of prolonged immobilisation with delay to current paradigms that advocate immediate weight bearing, early motion, and progressive strengthening and NMT (Bien et al., 2015; Hewett et al., 2013). However, despite these efforts, musculature weakness of the quadriceps (Lewek et al., 2005; Drechsler et al., 2006), impaired movement pattern (Paterno et al., 2007; Hartigan et al., 2009; Hart et al., 2010), abnormal neuromuscular control (Friden et al., 2001; Williams et al., 2005; Vairo et al., 2008; Paterno et al., 2010; Melick et al., 2016) and difficulty returning to sports are common for several months after ACLR (Hartigan et al., 2010; Ardern et al., 2011).

One factor may be that rehabilitation after ACLR mostly focuses on post-operative impairments of the involved limb and may neglect to address modifiable risk factors movement mechanics in both limbs in those athletes after ACLR (Kruse et al., 2012; Hewett et al., 2013; Paterno et al., 2015; Nyland et al., 2016; Paschos et al., 2017). The long-term benefits of an effective rehabilitation program may also be realised, both by the full restoration of functional performance and by the improved ability of these individuals to maintain lifetime activity participation without disability knee symptoms (DiStasi et al., 2013). Abnormal neuromuscular and biomechanical patterns are commonly seen up to several years after ACLR (Hartiga et al., 2009; Paterno et al., 2010; Hart et al., 2010; Roewer et al., 2011; DiStasi et al., 2013) and may help explain the high rate of second ACL injuries. The persistent deficits in the neuromuscular aspects following ACLR have been directly implicated in the risk of a second ACL injury (Paterno et al., 2010; DiStasi et al., 2012).

2.5.5. Relationship between biomechanical parameters during different functional tasks.

Jones and colleagues (2014) examined the relationship between SLL, 90° cutting and pivoting (180° turn) in 20 female football athletes. The authors reported strong association for peak knee valgus angle across the study tasks (r=0.63-0.86). In addition, a moderate association between SLL and cutting tasks (r=0.46), cutting and pivoting tasks (r=0.56) and SLL and pivoting tasks (r=0.43) for peak knee valgus moments values was reported. However, the study results were only based on data from female football athlete's population and it's unclear whether the study finding is applicable to other populations.

Furthermore, Whatman et al. (2011), investigated the association between unilateral and bilateral tasks (Single and bilateral leg squat, Lunge, Hop-lunge and Step-down) with jogging. The study assessed the correlation in frontal and transverse plane for hip, knee and ankle joints in terms of 3D motion analysis. The authors reported moderate to strong correlation between kinematic variables recorded during the study functional tasks in relation to jogging (r=0.53-0.93) (Whatman et al., 2011). Moreover, similar relationships between functional tasks, were also observed in a study by Harty et al. (2011), which examined knee frontal plane kinematics and kinetics in female athletes. The authors reported a strong correlation for knee valgus motion between Step-down, SLL and DVJ tasks. However, a moderate strong correlation for knee valgus moments was observed.

Alenezi et al. (2014) evaluated the correlation between four functional tasks included SLS, SLL, 90° cutting and running in ninety male and female recreational athletes (age 26.8 ± 4.7 years). The authors reported knee valgus angle during SLS task showed strong correlation with SLL, running and cutting (r=0.62, r=0.59, r=0.57, respectively). Moreover, the correlation strength was much higher when applied to female athletes (r=0.75, r=0.51, r=0.65, respectively). On the other hand, knee valgus moments, showed a weak correlation with SLS, SLL and running (r=0.25-0.5). Furthermore, no correlation was found between knee valgus moments during SLS, SLL and cutting (r=0.1-0.06). In regarding, hip adduction angle during the SLS task, showed moderate correlation with SLL, running and cutting tasks (r=0.42, r=0.48, r=0.40, respectively), whereas, hip adduction moments recorded small to moderate correlation between the previously mentioned tasks (r=0.21-0.41). Across all study tasks, knee valgus moment showed small to moderate correlation (r=0.15-0.5). This could be due to different technical parameters in each task which will affect knee valgus moments, such as foot progression angle which is the angle of foot orientation during initial contact relative to the original travel direction (Alenezi et al., 2014). The knee valgus moment has been reported to have significant correlation with foot progression angle (r=0.89, p=0.01) (Pollard et al., 2007). The study by Aenezi et al. (2014) had a number of limitations related to tasks standardization, these include the squat depth, running and cutting velocity. The author also only investigated the right lower limb.

An understanding of how the risk factors behave under different task condtions might provide better insights into possible high risk motion. This could potentially decrease the time and the number of functional tasks required in studies. Thus, avoid the need to perform many and/or greater difficulty functional tasks for screening, as just one easy task could be efficient to give an idea of which individuals may exhibit poor movement strategies related to a number of other complex functional tasks.

In summary, ACL injuries are the result of many factors such as anatomical, hormonal, neuromuscular control, and biomechanical. Whilst, many of these are not modifiable, the focus for any intervention to reduce the incidence of NCACL would lie with the modifiable risk factors. A lack of neuromuscular control and lower extremity strength is considered the most modifiable factors (Myer et al., 2009; Volpi et al., 2016). Therefore, researching these modifiable risk factors should be prioritized to enable the development of more effective interventions (Myer et al., 2009; Volpi et al., 2016). Several intervention studies have shown that lower extremity biomechanics can be altered by applying an appropriate NMT intervention (Caraffa et al., 1996: Hewett et al., 1999: Soderman et al., 2000; Myklebust et al., 2003; Mandelbaum et al., 2005: Pfeiffer et al., 2006; Gilchrist et al., 2008; Steffen et al., 2008; Pasanen et al., 2008; LaBella et al., 2011; Walden et al., 2012).

Literature review.

Search strategy: A systematic electronic database search was performed in the following electronic databases; Science Direct, PubMed, CINAHL, SCOPUS, SPORTDiscus, Web of Science, Cochrane Libraries, Sport Discuss and Google Scholar databases. All databases were searched in the English language from the earliest records available, for relevant journal articles published until May 2018. including human subjects. A manual review of relevant articles, authors, and journals, including bibliographies was performed from identified articles.

The following key words were utilized: ACL injury, Female athletes, NMT, Neuromuscular control, ACL injury prevention, AposTherapy system, Unstable footwear. The reference lists of the relevant studies were also reviewed to identify other potentially relevant studies.

2.6 Risk mitigation programs for ACL injury.

From an epidemiological perspective, applying risk mitigation of musculoskeletal condition may include strategies aimed at reducing the risk of acute and chronic musculoskeletal injuries such as ACL injury in susceptible populations (primary prevention) and/or incorporation of strategies aimed at slowing down or reducing the risk of reinjury (e.g., rupture of graft at ipsilateral knee and/or second ACL injury at the contralateral knee) in individual who previously sustained a primary musculoskeletal injury such as primary ACL injury (secondary prevention) (Whittaker et al., 2017).

Studies have documented that risk factors related to neuromuscular control have the potential to be mitigated. This may reduce the risk of sustaining an ACL injury (Griffin et al., 2005; Hewett et al., 2006; Hewett et al., 2007; Sugimoto et al., 2012; Volpi et al., 2016). It has been suggested that poor muscular protection exhibited by female athletes may be one of the potential factors placing them at a high risk of sustaining an ACL injury. Thus, implementing an intervention program that could develop muscular protection of the knee joint and correct the lower limb aligament may decrease the incidence rate of ACL injury in high-risk female athletes (Sugimoto et al., 2016; Hewett et al., 2016).

2.6.1 Intervention programs for reducing ACL injury rate.

Since the 1990s several studies (Table 2-1) have been performed to assess the ability of NMT interventions to prevent ACL injury and other lower-limb injuries.

Table 2- 1: Summary of prevention intervention for reducing ACL injury rates.

Author	study sample	training program	frequency and duration	outcomes
Caraffa et al. (1996)	600 M Semi-professional football players 17-25 yrs	Balance training, supervised	20 min 3 times/week /30days, pre-season for 3 seasons	Significant reduction in ACL injury in iv gp
Hewett et al. (1999)	434 M cont gp 463 F cont gp 366 F IV gp Basketball, handball volley ball players.14-18 yrs	Plyometric, Strength, Feedback, Stretch.	3-time week for 90-120 min sessions for 6 weeks	Significant reduction in NCACL injury in F iv gp vs f cont
Heidt et al. (2000)	300 F football players (258 cont gp;42 iv gp),14-18 yrs	FATP program: Agility, speed, strength, plyometric, flexibility	7 weeks .3 times per week. 75 min session	Overall decrease in ACL injury but not significant.8 ACL in cont gp vs 1 iv gp
Soderman et al. (2000)	100 F cont gp;121 F iv gp. 20.5±5.4 yrs	Balance training	15min daily for 30days than 3 times week for season	↑ in ACL injry in iv gp. 1 NCACL in cont gp vs 4 iv gp
Myklebust et al. (2003)	942 F cont gp1st yr, 855 F iv gp2nd yr, 850 F iv gp3r yr 18 ±2yrs	Balance, Feedback, Stretching training	15 min three times week for 5-7 weeks than drop to once/week	Significant decrease in NCACL in iv gps
Olsen et al. (2005)	1837 handball players (808 F and 150 M iv gp; 778 F and 101 M cont gp). 15-17 yrs	Warm-up; balance , strength , landing techniques	15 consecutive session and then once a week during the remainder of the season	Overall ↓in ACL injury but not significant Cont 9 ACLvs IV 3 ACL injury
Mandelbaum et al. (2005)	3818 F cont gp 1885 F IV gp football players.14-18 yrs	PEP program :strength, agility, stretching, plyometric training	Warm-up 20 min for 3 times week for 12 weeks at season	Significant decrease in NCACL injury :88% and 74% in the 1st and 2nd year, respectively
Petersen et al. (2005)	F Handball players (134 iv gp ;142 cont gp).19±1yrs	Balance, education and plyometric	10 min for 3-time week during per-season. once at	Overall decrease in ACL injury but not

			season	significant Cont 5 vs iv 1 ACL injury
Pfeiffer et al. (2006)	1439 F football, basketball, volleyball players (862 cont gp;577 iv gp). 13-17 yrs	Plyometric based exercise	20 min twice week for 9 weeks	No changes in ACL injury incidence (3ACL injury each gp)
Gilchrist et al. (2008)	1435 F foot players (852 cont gp;583 cont gp). 17-20 yrs	PEP program: strength, agility, stretching, plyometric training	20 min 3 days week for 12 week in and off season	High decrease NCACL (3.3 times less than cont gp) but not significant At 2nd year show sign ↓ACL inj (cont 5 vs 0 iv ACL inj)
Pasanen et al. (2008)	457 F Floorball players (201cont gp;256 iv gp). 13-17 yrs	Plyometric, balance strengthening, running techniques	warm up 20-30 min .2-3 times/week pre-season than once/week season	66% ↓ of leg injuries No sign changes in ACL injury incidence
Steffen et al. (2008)	947 F cont gp;1073 F iv gp football players.13-17 yrs	FIFA 11 program: balance, agility core stability, strengthening	warm up, start with 15 consective daily session than once/weekmin rest of the season	no sign changes in injury rats between iv and cont gps (cont 5vs iv 4 ACL inj) Low compliance rate
Kiani et al. (2010)	1506 F Football payers .13-15 yrs	Balance, core stability, Strengthening, Injury risk education (HPT Harmoknee preventive program)	20 min twice week for 16 weeks than once/week for 24 weeks	Sign ↓ in ACL injury incidence per 1000 hr AE in iv gp. 5 ACL injury in cont gp vs 0 iv gp
LaBella et al. (2011)	855 F Basketball, football players (348 cont gp ; 462 iv gp).16.2±1.5 yrs	KIPP program: balance, core-strenght, , polymeric, land technique	20 min session, 3 times week for 13 weeks	Drop in ACL injury incidence per 1000 hr AE in IV gp. 6 ACL injury in cont gp vs 2 iv gp
Walden et al. (2012)	2085 F cont gp;2479 F iv gp football players. 12-17 yrs	Balance, core stability while focus on knee alignments during jumping	15 min session. twice week for 7 months	Sig ↓ in NCACL injuries.14 ACL injury in cont gp vs 7 iv gp

Cont. gp: Control groups. iv gp: Intervention group. F: Females participants. M: Male participants. ACL: Anterior cruciate ligament. NCACL: non-contact Anterior cruciate ligament. ↓: decrease. AE: Athletic exposure. PEP: prevention injury, enhance performance. FATP: Frappier Acceleration Training program. KIPP: knee injury prevention program.

Some NMT implement single or limited elements in their intervention programs such as balance exercise, plyometric exercise or a combination of both exercises (Caraffa et al., 1996;

Soderman et al., 2000; Myklebust et al., 2003; Petersen et al., 2005; Pfeiffer et al., 2006). Other NMT intervention programs have more comprehensive approaches comprising different types of exercise such as strength, stretching, plyometric, and balance exercises (Hewett et al., 1999; Heidt et al., 2000; Olsen et al., 2005; Mandelbaum et al., 2005; Steffen et al., 2008; Kiani et al., 2010; LaBella et al., 2011; Walden et al., 2012).

Sportsmetrics (Hewett et al., 1999), FATP (Frappier Acceleration Training program) (Heidt et al., 2000), PEP (prevent injury and enhance performance) training programs (Mandelbaum et al., 2005; Gilchrist et al., 2008), FIFI 11 and 11+ programs (Steffen et al., 2008; Soligard et al., 2008) along with other intervention programs are examples of programs that implement different types of exercise. In addition, some NMT includes sport-specific training HPT (Harmoknee preventive programe) (Kaini et al., 2010), KIPP (knee ligamanr prevention program) (LaBella et al., 2011) whereas other intervention programs adapt performance enhancement as well as injury prevention (Steffen et al., 2008; Walden et al., 2012). However, the prophylactic influence of NMT programs until now has demonstrated mixed results (Sugimoto et al., 2016; Stevenson et al., 2015). The combination of insufficient neuromuscular recruitment and high-risk landing patterns will all lead to higher ACL stress (Stevenson et al., 2015; LaBella et al., 2014; Voskanian et al., 2013; Renstrom et al., 2008). Several studies have investigated the preventative effect of ACL injury prevention programs, which are hypothesized to address the risk of neuromuscular recruitment and biomechanical patterns (Voskanian et al., 2013; LaBella et al., 2014; Stevenson et al., 2015).

Griffin et al. (2000) reported the work of Henning (1990), who incorporated intervention programs on female basketball players over the course of eight years. The study concluded that an increase in NCACL injury in female athletes is linked to knee position and muscular-recruitment patterns during dynamic movements. The NMT in the study was performed for 4–6 weeks to gain prophylactic effects. It focused on enhancing athlete’s techniques with flexed knee landing, acceleration, three step-stop with flexed knee, and inside leg-around turns. The author reported an 89% drop in ACL injuries in the intervention group, based on improved player techniques (Griffin et al., 2000). The author concluded that the common ACL injury mechanisms were straight-knee landing (28%), cutting and pivoting (29%) and one-step stop while knee is hyperextended (26%). Therefore, it was logical to suggest programs that focused on avoiding high-risk situations by modifying the execution technique of sport movements.

Caraffa et al. (1996) investigated the effects of incorporating a NMT balance program to reduce the risks of ACL injury in male semi-professional and amateur football players. The program was conduct for 30 days pre-season for 3 days/week for 20 min and was supervised. They were asked to balance on one leg using a balance board with progressive difficulty, under supervision. The study reported 70 ACL injuries in the control group compared with just 10 in the intervention group, which indicated a significant reduction in ACL injury risk in the intervention group.

Hewett et al. (1999) conducted a study that was one of the first to investigate the effects of implementing NMT on female athlete's ACL injury incidence. The study population was of high-school female football, volleyball and basketball athletes. The intervention group comprised female participants (366 participants). There were two control groups, one comprised female athletes (463 participants), and the other male athletes (434 participants). The intervention program implemented different exercise elements: plyometric, strength, stretching, and correcting the landing patterns. The program was followed by a 6-week pre-season period, where each session lasted for around 90–120 minutes and was performed three days a week. The groups were evaluated regarding ACL injury incidence in female athletes throughout the season. The authors reported that the incidence of knee injuries in the trained female athletes was not significantly different from that in untrained male athletes (p=0.8). However, differennces in the NCACL injury rate between female groups was significantly (p=0.01) with the no NCACL injury in trained female athletes group compared with 8 NCACL injuries in the untrained female athletes group.

This intervention program has been modified and updated throughout the years and been implemented as "Sportsmetrics". Nevertheless, the study by Hewett et al. (1999) showed very promising results when NMT is applied to reduce NCACL injury in female athletes. However, it was noticed there was uneven distribution of participants in the different sports between the control and intervention groups, as more female football and basketball athletes were recruited in the intervention group than in the control group. As it has been documented that football and basketball players have the highest ACL injury incidence among high-school female athletes, this uneven distribution of female athletes regarding type of sport participation may produce a bias effect. It shows that intervention group athletes have higher reduction rates than could be achieved, potentially exaggerating the benefits of the intervention program. However, the design intervention was used before by the same author

(Hewett et al., 1996), which successfully managed to target and improve the dynamic movement patterns and muscle imbalance. It demonstrated that female athletes who participated in NMT programs showed more improvement in dynamic knee stability than did females athletes who did not participate in similar programs.

A study by Heidt et al. (2000) incorporated a seven-week prevention program (FATP) that was 75 minutes long. A custom-made agility and speed exercise program was applied to female football players for a period of 7 weeks 3 sessions per week. The FATP (Heidt et al., 2000), was the only NMT program which used Acceleration-speed running as part of its multi-component training program. Specifically, a treadmill was used with the ability to incline to 40° enabling the athletes to perform incline sprints at a higher physical load. The intervention was incorporated during pre-season. There was an overall trend toward of reduction of ACL injuries in the intervention group (1 ACL injurey), when compared with the control group (8 ACL injuriy).

Soderman et al. (2000) studied the effects of implementing a NMT program in female footballers, where each female athlete was given her own balance board and instructed to use it on a daily basis for the first 30 days, and then for three days a week for the rest of the competition season. Participants were asked to balance on one leg using dyna discs and balance boards for 10–15 minutes each session. The study showed a higher incidence of ACL injury per 1000 hours of athletic exposure (AE) in the intervention group (0.68 per 1000 hours AE) while the control group had a lower rate (0.12 per 1000 hours AE). This demonstrated a trend toward increased ACL injury incidence in the intervention group. The study results showed no significant difference between the study groups, which was explained by the high dropout rates and very low adherence rates. In addition, there was no supervision as the training was performed from home. However, the study did not establish whether the ACL injuries reported were sustained through contact or non-contact mechanisms.

In a study by Myklebust et al. (2003) performed a NMT intervention on cohort of Norwegian female team handball players. The study was conducted over three years, where the first year was to observe ACL injuries in the control group. After the second and third years the NMT was implemented to the intervention groups. The intervention program was practised for 5–7 weeks at pre-season for three times a week for 15 minutes a session after which NMT was dropped to once a week for the rest of the session. The intervention program included three different types of exercise, and needed to be performed for 5 minutes each i.e. 5 minutes of floor exercise, 5 minutes on the wobble board, and 5 minutes on the balance mate with each athlete working with a training partner to provide technique feedback. Moreover, sport-specific exercise was added in the second intervention year as manoeuvres with higher levels of demand incorporated (Myklebust et al., 2003). Even though there was a trend towards a reduction in the ACL injury rate in the intervention group, the authors reported that the overall level of compliance was not high (26%). Interestingly, when looking at the subgroup, which included elite-level athletes, there was a significant difference in the ACL injury-rate reduction in the intervention group compared with the control group. The outcome could be related to the much higher compliance level shown in the elite athlete subgroup, which may be associated with the level of their discipline, when compared with other athletes from lower divisions. Moreover, if the difference in particular NCACL injury incidences sustained to be examined, it was found there was in fact a significantly lower rate of NCACL injuries between the intervention and control groups. Thus, when taken in the right context, it can be concluded that the program had the potential to significantly reduce the risk of NCACL injuries in competitive-level female team handball players.

Another study which showed promising result was conducted by Mandelbaum et al. (2005), who implemented an NMT intervention program known as the PEP program (Prevent injury and Enhance Performance) on female football players. The duration of the intervention was 12 weeks during the competition season, where the training was performed in 20-minute sessions two to three times a week. This intervention program was designed to replace the football team's routin warm-up during practice. The PEP program was introduced by presenting an educational video on unsafe and safe landing techniques. Also, the participants did strengthening, stretching, plyometric and football-specific agility drills. The intervention demonstrated a significant reduction in NCACL injury rates, as in the first year there was a drop of 88% and in the second year a 74% overall reduction. The PEP program aimed to address the potential deficits in the muscular recruitment pattern dynamic control and muscle strength that play a critical role in dynamic stability of the knee joints. The compliance rate was high due to the program being designed as a warm-up with the effect of neuromuscular fatigue not preventing any prophylactic influence of the intervention program (Mandelbaum et al., 2005). However, it was a complex program and yet not all coaches or athletes would be persuaded to incorporated this exercise in replace to their normal warm-up routine.

Moreover, in future studies which utilised PEP program did not demonstrate similar significant outcomes (Gilchrist et al., 2008).

Olsen et al. (2005) investigated the effect of the study NMT intervention program on female team handball players. The intervention consisted of four sets of exercises lasting 15–20 minutes each session. The NMT program focused on executing proper biomechanics during jumping and landing pattern feedback on landing technique and core stability. Athletes participating in the intervention group were instructed to complete 15 consecutive training sessions at the beginning of the season, followed by one session a week for the rest of the season. The study reported a high compliance rate of 87%, which was considered one of the programs strengths. It proposed that the program be incorporated into handball team warm-ups, which would make it easier to be performed at every training session. The results showed a trend towards reduction in ACL injury incidence in the intervention group (0.03 per 1000 hours AE) compared with (0.10 per 1000 hours AE) in the control group (Olsen et al., 2005).

Petersen el al. (2005), evaluated the efficiency of the NMT intervention included balance board and plyometric training that educated safe landing patterns and prevention strategies. The program was incorporated in 10-minute sessions three times a week during pre-season and then dropped to once a week in the competition season. When comparing the intervention group athletes with age and skill-matched controls, there was a trend toward reduced ACL incidence in the intervention group (0.04 per 1000 hours AE) compared to the control group (0.21 per 1000 hour AE). In a study by Pfeiffer et al. (2006), the authors incorporated a NMT program based on a plyometric-based exercise program implemented on basketball, volleyball, and football players for two 20-minute sessions per week for nine weeks. This plyometric-based exercise program showed an ACL injury incidence rate of 0.08 per 1000 hour AE in the intervention group and 0.04 per 1000 hour AE in the control group. This showed no significant defferences in ACL injury rate between study groups, which could be because it used one exercise element in its intervention program. The dose and frequency of this program may not been sufficient to develop neuromuscler adaptations (Sugimoto et al., 2014).

Gilchrist et al. (2008) investigated the effect of a PEP program on NCAA division-one female football players in a randomised control trial. The study applied the PEP program to female footballers who had been previously mentioned in the study by Mandelbaum et al.

(2005). The program was performed for 20 minutes three times a week for 12 weeks. The ACL injury incidence in the intervention group was 0.20 per 1000 hour AE, whereas in the control group the ACL injury incidence was 0.34 per 1000 hours AE. The outcome of the study showed a trend towards reduced ACL injury rates. The study did not achieve statistical significantly differences at its first year intervention. However, when evaluating results at the 2nd year, there were a significant reduction of ACL injury rates in the intervention group (5 ACL injuries in the control group vs 0 ACL injuries in the intervention group) were 3 of the 5 ACL injuries at the control group were NCACL. At the seconed year of the study intervention subgroup analysis did show a significant benefit. When the authors looked at ACL injury incidences in study subgroups for intervention and control group during practices vs game, early vs late in season and athletes with or without a history of primary ACL injury. In addition, the study NMT program significantly lowered the incidence of NCACL injuries in athletes with history of primary ACL injury (Gilchrist et al., 2008). This study concluded that NMT (PEP) did significantly reduce the incidence of ACL injury sustained in practices and late in the season. This may be caused by the cumulative effect of the training program and suggest that the PEP program took some time to have an effect.

The PEP program was assessed for its effect on both lower limb biomechanical and injury rates (Mandelbaum et al., 2005; Pollard et al., 2006b; Gilchrist et al., 2008). The PEP program although successful in Mandelbaum et al. (2005) approached but did not reach significantly when used in another study by Gilchrist et al. (2008) only till the second year of the intervention, possibly due to the fact that it included athletes in their late teens (18-20 years). In addition, PEP in the study by Mandelbaum et al. (2005), the enrolment method of participants might be a source of bias, as a result from participants not being randomized selected (selection bias) and they voluntarily enrolled to the intervention program (motivation bias). Pollard et al.(2006b) determined the biomechanical changes in lower limb movement pattern after female athletes football players participate in the study PEP during their warm-up during their usual practise, and showed reduction in hip adduction angle, while performing drop jump landing task (DVJ).

A cluster-randomised control trial studied the influence of a structured warm-up program called FIFA “11+” (Steffen et al., 2008). The “11+” program consisted of plyometric, balance core stability, and hamstring strength. The duration for every session was 15 minutes’ practice on a daily basis for the first 30 days, and then once a week for the rest of the season for the remaining seven and a half months. The study reported a slight trend in ACL injury incidence reduction in the intervention group compared with the control group (Steffen et al., 2008). The FIFA 11 NMT warm-up program utilized effective training components but began training for limited amount of time (15 consecutive sessions), which may not be enough time for achieving desirable neuromuscular adaptation, which was shown with the program filing to significantly reducing ACL injury incidence in the study intervention group (Steffen et al., 2008).It has been reported that a NMT prevention program needs to be performed more than once a week for at least 6 weeks to achieve the required neuromuscular adaption changes (Hewett et al., 2006).

Pasanen et al. (2008), study the effect of NMT program on 457 female footballers' athletes. There were 256 participants in the intervention group and 201 participants in the control group. A multi-component training program was incorporated included running, balance, plyometric strength, stretching training for athletes with limited flexibility training included. Education and feedback on the right technique was also include in the study NMT program. The training sessions were performed for 20-30 min 2-3 times a week during pre-season, then once a week at the competition season. The training started in the pre-season and continued in-season, with participants of both professional and amateur levels in their early adult (over 20 years). The intervention program was implanted in the team warm-up schedule. It showed a trend of NCACL injury incidence reduction, with a 66% lower risk of sustaining an ACL injury reported in female athletes who participated in the intervention. Although there was no significant reduction in ACL injury incidence rates in the intervention group. A significant fewer reduction in non-contact leg injuries in general was achieved in the intervention group (Pasanen et al., 2008).

A study by Kiani et al. (2010) incorporated NMT program on female footballers. The program (HPT) was replacing the routine warm-up and consisted of a number of different components with strengthening of the lower limbs, balance exercise, core stability injury risk education, and running warm-up. Each session was performed for 20 minutes and did not require no additional equipment. The athletes were instructed to practise the intervention twice a week for the first four months in the pre-session, and then drop to once a week for the next six months in the competition season. A monthly newsletter was mailed to the team to maintain high level of motivation and compliance to the program. The authors reported that the incidence rate of acute non-contact knee injuries dropped by 90%. In addition, there was no ACL injury incidence recorded in the intervention group, whereas in the control group 0.08 per 1000 hours AE ACL incidence were recorded, showing significant a trend toward reduction in ACL injury incidence.

LaBella et al. (2011) investigated the effects of NMT warm-up program on ACL incidence in high-school female athletes who participated in basketball and football. The intervention program was implemented three times a week for 13 weeks. The program consisted of progressive strength, plyometric, balance, and agility exercises with the emphasis on applying proper safe landing patterns. The program was known as KIPP (Knee Injury Prevention Program). The study reported a 56% reduction in non-contact lower extremity injuries in the intervention group compared with the control group. Regarding NCACL injuries, there were a total of six ACL injuries in the control group compared with two ACL injuries in the intervention group. It can be interpreted that female athletes recruited to the NMT program had 73.4% less risk of suffering an NCACL injury than female athletes who did not participate in the program.

Walden el al. (2012) conducted a study to observe the effects of a NMT program on female football players with an average number of participants in both the intervention (2479 participants) and control (2085 participants) groups. The study implemented a NMT warm-up program to practise for 15 minutes twice a week during the whole football competition season (seven months). The elements incorporated in the program were balance exercise and core stability with the focus on proper knee alignment. The exercise program included four steps of progressive difficulty and included six exercises, which were single leg squat, bilateral leg squat, pelvic lift, lunge, bench, and plyometric. The NMT resulted in seven female athletes sustaining an ACL injury compared with 14 female athletes sustaining an ACL injury in the control group, showing a 1.64% reduction in NCACL injury risk in the intervention group. The authors concluded that NMT showed a significant reduction in the ACL injury rate in adolescent female football athletes.

In summary, studies have showed statistically significant decreases in the incidence of ACL injury using pre-season NMT programs (Hewett et al., 1999; Myklebust et al., 2003; Mandelbaum et al. 2005; Gilchrist et al., 2008; Walden et al., 2012). However, some intervention programs showed a trend towards increases in ACL injury incidences in the intervention groups (Soderman el al., 2000; Pfeiffer et al., 2006), where they used NMT during the regular competition season only. Despite initial evidence indicating that NMT programs has been successful in improving the biomechanical risk factors for ACL, there is still disparity between positive laboratory results demonstrated with NMT programs and the actual effect on injury outcomes in high-risk female athlete population, which suggested a missing link between current published research and clinical application for prevention intervention programs (Myer et al., 2007; Finch et al., 2014; Sugimoto et al., 2014; Hewett et al., 2016). Examining whether neuromuscular motor control learning can be transferred from laboratory conditions to the competitive field raised the issue whether current utilized learning techniques may not be sufficient to promote unexpected and automatic movement (Benjaminse and Otten, 2011; Michaelidis et al., 2014).

One proposed explanation for the disparity between laboratory results and incidence outcomes may be related to unrealistic time commitment required 75-120 min (Hewett et al., 1999; Heidt et al., 2000). In addition, the complexity and difficulty in implementing of the techniques previously found to be successful in changing injury risk may be deterring athletes and/or the coach to utilise them (Sugimoto et al., 2016; Stevenson et al., 2015: LaBela et al., 2014)). Even though, some researchers tried to implement shorter NMT into team warm up routine, which would element large time commitment and may be perceived by athletes or coaches to detract them from implementing sport specific skill training, such arrangement could deter athletes and coaches from incorporation NMT into their pre-season or in-season conditioning programs (Sugimoto et al., 2016; Stevenson et al., 2015).

Moreover, many programs have implemented high intensity exercise such as strength and jump base exercise in their programs which in return may result in increased risk of fatigue injury relate which may have negative influence in return (LaBella et al.,2011; Kiani et al., 2010; Pasanen et al., 2008; Gilchrist et al., 2008; Mandelbaum et al., 2005). Furthermore, some intervention programs managed to introduce short NMT (15-20 min sessions) with low intensity based training (Myklebust et al., 2003) which showed a strong trend towards reduction of ACL injury incidence, but they did report low compliance rates. Moreover, other studies which incorporated short simple programs, did not manage to show promising outcomes (Pfeiffer et al., 2006; Soderman et al., 2000).

2.6.2 Modifiable risk factors intervention programs.

Several biomechanical studies (Table 2-2) have investigated the effect of different neuromuscular training (NMT) programs on modifiable risk factors for NCACL injuries. The majority of these are in female athletes due to the greater incidence of NCACL injury reported in the female athletic population compared with male athletes (Monajati et al., 2016; Myer et al., 2013).

Table 2- 2: Summary of ACL injury risk modifying intervention programs.

Author	**study sample**	**training program**	**frequency and duration**	**outcomes**
Hewett et al. (1996)	11 F high school volleyball,15±0.5 yrs . 9 M high school volleyball , 15±0.3 yrs	Jump training program with focus on landing mechanics , with stretching and strengthening	6 weeks 3 times per week for 120 min session	50% ↓ Knee valgus , varus moments ,22%↓VGRF, 10%↑, 26% ↑H:Q muscle peak torque ration
Irmischer et al. (2004)	28 F recreational athletes(14 iv gp ;14 n cont gp), 24±4yrs	Low-intensity jumping based exercise (KLIP)	9 weeks, twice per week , 20 min session	Sign ↓vGRF(RFD and Fp).Mild↑ Jump height
Lephart et al. (2005)	27F (14 plyometric gp ;13 resistance gp) . 14.3±1.3 yrs high school	1st IV gp plyometric; plyometric and agility exercise 2nd IV gp resistance; resistance ,flexibility ,balance exercise	8 weeks, 3 times per week , 30 min session	↑Q isokinetic strength ,↑HFA,↑KFA ,↑Gluteus medius pre-active and reactive levels in both groups
Myer et al. (2005)	53 F high school athletes (12 cont gp; 41 iv gp).13-17 yrs	Strengthening, balance , core-strengthening and plyometric	6 weeks, 3 times per week , 90 min session	Sign ↑ KFA ,↓ KVM during DVJ and ↑performance measures .
Grandstand et al. (2006)	21 F football players (12 iv gp ; 9 cont gp), 9-11 yrs	Sports metrics WIPP: agility, strengthening, plyometric, stretching	8 weeks, twice per week ,60min session	No change in Knee separation distance post training and No difference between groups found
Myer et al. (2006)	18 F high school athletes(8 plyometric gp and 10 Balance gp). 15.9±0.8 yrs for Plyometric gp ; 15.6±1.2 yrs for	1st IV gp plyometric 2nd IV gp balance each group performed agility, strength warm up	6 weeks,3 time per week, 90 min session	Both groups ↓KVA during SLL. ↓HAD&AEA during DVJ. ↑ KFAfor Plyometric gp during DVJ. ↑KFA during SLL for Balance gp
Pollard et al. (2006)	26 F football players ,14-17 yrs	PEP program; stretching, strengthening, plyometric, agility exercise	16 week, 2-3 times per week, 20 min session	DVJ:↑HPAbd,↓HIRA,
Myer et al. (2007)	29 F (18 uv gp ; 11 cont gp) high school football, basketball players .	Core stability, balance, strengthen, plyometric	6 weeks, 3 times for 90 min session	↓ KVM during DVJ in high risk category subjects in comer to
Kato et al. (2008)	20 F basketball players, (20.4±1.0 yrs)	Strengthening, jump-landing, balance, feedback	4 weeks, 3 times per week ,20 min	↓ KVA Stop jump task

Chappell& Limpisvasti. (2008)	30 F (18 basketball and 12 football), 19±1.2 yrs	Core strengthening, balance, plyometric training with feedback	6 weeks, daily for 10-15 min session	DVJ: ↓HAA,↑KFA. Stop-jump:↓HFA,↓KPVM, ↓KFM
Herman et al. (2008)	66 F (33 cont gp;33 F IV gp). 18-30 yrs	Strengthen focus program for Glut max, med, Q, H. muscles	9weeks ,3 times per week, 45 min session.	NS in hip and knee angle and moments durong 3 stop-jump tasks
Lim et al. (2009)	22 F basketball players (10 iv gp ,10 cont gp), 15-17 yrs	Modified version of PEP program; stretching, strengthening, plyometric, agility exercise	8 weeks, daily for 20 min	↑ KPFA ,↑ KFM,↓KVM, ↓ QS and ↑H activity during RVJ task
Ortiz et al. (2010)	30 F football player, 14-15 years	Flexibility, strengthening, plyometric exercise for intervention gp Cont gp continue its regular practice and game	6 week , twice week for 20-25 min(SIPP)	SLDJ:↑KVM, ↑KEM ↑ Q strength
Distefano et al. (2010)	65 Football players (39 Boys ;28 Girls) 10±1 years	Paediatrics traditional IPP(PEP): dynamic starching, plyometric, strengthening	9 weeks, 3 times per week .15 min session	↑ Vertical jump hights.↓anterior – posterior to stabilization
Herrington et al. (2010)	15 F Basketball players 19.1± 6.1 years	Progressive jumping training from bilateral to unilateral activities, Feedback, and technical correction	4 weeks, 3 times week for 15 min	DJ: ↓2D FPPA at both R and L side
Vescovi& Vanheest. (2010)	31 F football players 13-18 year	PEP program ; stretching, strengthening, plyometric, agility exercise	12 weeks, 3 time a week	No improvement in liner sprint performance or CMJ task
Barendrecht et al. (2011)	80, Handball players (49 iv gp,31 cont gp), 13-19yrs	Agility, balance, strengthening, plyometric exercise	10 weeks, twice a week	Significant ↑ in knee separation distance in iv gp , NS in KFA during DVJ
Lindblom et al. (2012)	52 F football player(28 iv gp ; 24 cont gp),12-16 year	Warm-up program (Knakontroll); Balance, core stability while focus on knee alignments	11 week, twice per week 15 min session.	SEBT, Sprint 10 and 20 m , Agility test , 3 step jump were NO improvement observed in iv gp.(Low complaint in iv gp)
Steffen et al. (2013)	148 F football players,13-18 year	FIFA 11+ : Sprint, jump, agility exercise	18 weeks ,2-3 per week ,15 min session	Improve in Single leg balance and Anterior direction of the SEBT in field supervised subjects
Leporace et al. (2013)	15 M volleyball players ,13±0.7yrs	Core stability, balance, plyometric exercise	6 weeks, 3 time per week	No change in jump height or Knee and Hip Sagittal plane angles during double and single legged from landing for VJ

Letafatkar et al. (2015)	29 female recreations athletes (15 iv gp; 14 cont gp) 14.5±1.3yr	Perturbation training progression in six levels with increasing intensity and difficulty	6 weeks, 3times per week for 30-45 min sessions	Significant increase in medial muscular CCI and lateral CCI during SLL task at FF and FB phase
Thompson et al. (2017)	51 preadolescent female football players (28 iv gp ; 23 cont gp) 10-12 yrs	Strength, plyometric, agility. In 3 progressive difficulty levels F-MARC 11+ warm-up program	7-8 weeks, twice a week ,25 min sessions.	Reduction in hip add during SLL task. trend reduction of KVA and KVM during DVJ only ,but not change during SLL ,cutting tasks
Hopper et al. (2017)	23 F Netball players (13 iv gp ; 10 cont gp),, 12.2±0.9 yrs	Agility, plyometric, strengthen	6 week, 3 times week, 60 min session	Sign ↑KIRA during unilateral landing. Sign ↑bilateral knee marker distance during bilateral landing Sig↓ GRF in both task

Cont gp: Control groups. IV group: Intervention group. F: Females participants .M: Male participants. H: Hamstrings muscle. Q: Quadriceps muscle .VL: vastus lateralis. ST: Semitendinosus. BF: Biceps femoris. PEP: prevention injury, enhance performance. KVM: Knee valgus moments. KVA: Knee valgus angle. KFA: Knee flexion angle. KFM: Knee flexion moment. KEM: Knee extension moment. KIRM: Knee inter rotation moment. KIRA: Knee inter rotation angle. HFA: Hip flexion angle. HAA: Hip abduction angle. HIRA: Hip inter rotation angle.AEA: Ankle eversion angle. FPPA: Frontal plane projection angle. VJ; Vertical jump. DVJ: Drop vertical jump task. SLDJ: Single leg drop jump. SLL: Single legged landing task. Cutt: Side cutting task. RVJ: rebound-jump task SEBT: Star excursion balance test. CMJ: Countermovement jump. CCI: Co-contraction index. FF: Feedforward motor control phase. FB: Feedback motor control phase. KLIP: Knee ligament injury prevention. WIPP: Warm up injury prevention program. IPP: Injury prevention program. SIPP: Sport injury prevention program. PTP: Prevention training program. VGRF: Vertical ground reaction forces. RED: Rate of force development. Fp: Peak vertical impact forces. NS: Not significant. Sing: Significant. R: Right. L: Left.↑: increase. ↓: decrease.

Several intervention programs have demonstrated positive improvements biomechanical risk factors for NCACL, which included reducing knee valgus angles and moments, which aim to reduce the loads on ACL during sport manoeuvres (Hewett et al., 1996; Myer et al., 2005; Myer et al., 2006; Myer et al., 2007; Chappell and Limpisvasti, 2008; Cochrane et al., 2010; Herrington et al., 2010; Barendrecht et al., 2011; Thompson et al., 2017; Hopper et al., 2017). The majority of previously mentioned interventions incorporated various training modalities, such as balance, agility, strengthening, core stability, and plyometric. Therefore, it is unclear which training element may influence the modified risk factors for NCACL injury, although a number of studies have observed the effect of different single training elements on lower-limb biomechanics and neuromuscular control, which may reduce the risk of NCACL injury (Herrington et al., 2011; Cochrane et al., 2010; Herman et al., 2008; Myer et al., 2006).

Myer et al. (2006) performed a study on 18 female participants who were recruited into two intervention groups: a plyometric training group with 8 participants and a balance training group with 10 participants, the training program consisted of 18 training sessions over seven weeks with each session lasting 90 minutes. The effect of the training program showed task-specific results as knee valgus decreased during single-leg landing task (SLL) and the hip adduction angle and ankle eversion angle drop during drop vertical jump (DVJ) task. Interestingly, parameters outcomes at sagittal plane was task-specific too were increase in knee flexion angle during DVJ for the plyometric intervention group, whereas, knee flexion angle during SLL for the balance group (Myer et al.,2006). No differences were reported between the groups with the results of the study supporting both balance and plyometric training programs. In another study, Cochrane et al. (2010) investigated the effects of balance training and weight training on lower-extremities biomechanics when performing side-cutting manoeuvres. The study's sample population included 50 Australian Rules football players, who were randomly located into five different study groups and followed the intervention program three times a week for 12 weeks. The first group was the study control group, who just undertook their normal training regime. The second group performed balance training only. The third group did machine-weight-based training. The fourth group performed free-weight training only. Finally, the fifth group performed a combined training program, which included both balance and machine-weight training. The study reported that the participants who were included in the free-weight group did not show any changes, whereas the ones who participated in the balance-training group showed a reduction in knee valgus, flexion and rotation moments. The participants in the machine-weight groups only showed a decrease in knee valgus moments. The participants who trained in the balance and machine-weight only also showed a drop in knee flexion moments.

The improvement in biomechanical risk factors on more than one plane could be explained as balance training challenging the lower-limb joints in all three planes of motion, whereas strength training would mostly induce changes on a single plane, as shown in Cochrane et al. (2010). Herrington et al. (2010) reported a decrease in knee FPPA (frontal plane project angle) which been correlated to 3D knee valgus motion and loads (Willson and Davis, 2008; Gwynne and Curran, 2014; Herrington et al., 2017) in female basketball players who underwent a four-week plyometric-based training program, which was similar to the outcome previously reported in other intervention studies that used plyometric-based training interventions (Myer et al., 2005; Hewett et al., 1996). However, the intervention by Herrington et al. (2010) showed promising out comes in short term plyometric NMT program it required constant supervion and was no 3D motion anlayis data avalible.

Deficits in neuromuscular coordination and muscle strength within the muscles stabilizing the knee joint have been proposed to place a high stress on the ACL and potentially predisposing female athletes to ACL injury (Griffin et al., 2006; Hewett et al., 2009; Kiapour et al., 2014). Many intervention programs have based their concepts on modifying biomechanical risk factors by improving the level of neuromuscular control of the lower limbs (Voskania et al., 2013; Sugimoto et al., 2016). Throughout implementation of NMT in several studies incorporated with the aim of reducing the incidence of ACL in female athletes (Hewett et al., 2005; Stevenson et al., 2015) plyometric was a component of 80% of the NMT studies, balance training was 70% and strength training and flexibility accounted for 60% and 40%, respectively (Stevenson et al., 2015).

Although, studies have reported that NCACL injuries occur too fast to reflect muscle activation (17–40 milliseconds) after initial ground contact (Myer et al., 2005; Krosshang et al., 2007; Koga et al., 2010; Walden et al., 2015), NMT programs could implement alteration in neuromuscular patterns or pre-program safer movement patterns that may decrease ACL injury risk during landing or unexpected loads, or perturbations during sport movement (LaBella et al., 2014). With sufficient levels of neuromuscular control and balance of the lower-limb musculature, the knee joint would have the ability to avoid dynamic valgus by increasing dynamic knee stability while participating in competitive sport. Thus, the NCACL injury risk could be considerably reduced (LaBella et al., 2014). Multiple risk factors have been proposed as the underlying reasons for gender disparity in ACL injury when similar sports are being played, but several studies have suggested that neuromuscular control may be the most important of these, offering the best modification potential (Sugimoto et al., 2015; Monajati et al., 2016).

The changes in muscle recruitment pattern strategy that reduce dynamic joint stability in high-risk female athletes and potentially increase NCACL injury risk could be modified if female NMT is implemented in early to middle adolescence, when neuromuscular and biomechanical risk factors for NCACL injury start to be developed (Hewett et al., 2010; LaBella et al., 2014; Donnell-Fink et al., 2015). Poor neuromuscular adaption is thought to stem from gender discrepancy, as poor neuromuscular control and imbalanced muscular recruitment patterns develop biomechanical pattern risks while landing from a jump; therefore, there is an increased risk of sustaining an NCACL injury (Hewett et al., 2006; Guigliano et al., 2007; Ford et al., 2011). Recent studies have documented that mal-neuromuscular adaptation with imbalance recruitment patterns result in high-risk biomechanical pattern (high dynamic knee valgus) and may be corrected by participating in a NMT prevention program (Smith et al., 2012; Hewett et al., 2016; Monajati et al., 2016).

It has been suggested that the ideal intervention program will incorporate exercise and drills that emphasise muscle strengthening, balance, plyometric, stretching training as well as education and feedback regarding jump-landing techniques. It would be ideal to participate in a six-week period of NMT prior to the season, which could replace the traditional warm-up (Mandelbaum et al., 2005; Steffen et al., 2008; Distefano et al., 2010; Lindblom et al., 2012; Steffen et al., 2013; Thompson et al., 2017). Compliance with the intervention program is critical to the success of any NMT intervention aimed at preventing ACL injuries risk or incidence, it has been documented in the literature that when the overall adherence rate was higher than 66%, with an ACL injury reduction rate of 82% reported (Sugimoto et al., 2015). When the adherence rate dropped to less than 66% and 33%, the rates of ACL injury rate reduction were found to be 44% and 12%, respectively (Sugimoto et al., 2015).

Several studies have pointed out that a low compliance rate is considered a major limitation (Soderman et al., 2000; Myklebust et al., 2003; Steffen et al., 2008). It been documented that limitation of available NMT time was due to various reasons such as infrequent practice days, competition days and occasional academic commitment and holiday breaks (Sugimoto et al., 2012). Those previously mentioned reasons could possibly restrict the NMT programs from reaching its optimal potential (Sugimoto et al., 2012). In effort to enhance participant's adherent several studies that have implemented NMT programs within the pre-match or pre-practice warm-up routines and demonstrated a significant reduction in ACL injury incidence or showed a trend towards decreasing ACL injury incidents within their female athlete populations (Mandelbaum et al., 2005; Gilchrist et al., 2008; Kiani et al., 2010; Walden et al., 2012). Furthermore, others have made their programs desirable by showing the performance enhancement and skills development benefits when participating in the intervention program (Steffen et al., 2008; Soligard et al., 2008; LaBella et al., 2011). However, those measures did not show simillar success beyond the lab environment (Sugimoto et al., 2014, 2015).

In order to achieve the prophylactic effects and reduce the risk of sustaining NCACL injuries, athletes would need to participate in NMT on a regular basis (Sugimoto et al., 2015). The frequency and duration of NMT sessions were found to have a direct association with possible ACL injury reduction (Sugimoto et al., 2014, 2015). However, it is more challenging to implement programs with larger time commitments and would be difficult to sustain over a longer period (duration, frequency of intervention) (Sugimoto et al., 2014,2015). The time commitment of athletes themselves, athletic coaches and athletic trainers to implement and track NMT intervention programs, as well as considering their level of comfort, are all factors to be taken into consideration and weighed against potential benefits when considering any NMT program (Sugimoto et al., 2014; Stevenson et al., 2015).

In a systematic review study whcih reviewed 14 NMT programs that aimed at reducing ACL injury examined and analysed them based on the volume and frequency of NMT and its effect on ACL injury rates (Sugimoto et al., 2014). The systemic review study categorised the NMT programs depending on their frequency and volume into three different classifications: low (up to 15 minutes per week) moderate (15–30 minutes per week) and high (higher than 30 minutes per week) (Sugimoto et al., 2014). An inverse response was observed between NMT volume and the incidences of ACL injury by demonstrating that the more time athletes spend practising NMT the better reduction in NCACL injury rate was achieved (Sugimoto et al., 2014). The systemic review study concluded that to achieve the prophylactic effect, the NMT program should be performed at least 20 minutes per training session, several times a week, in pre-season as well as during season. This was essential in order to achieve the full prophylactic effect desired (Sugimoto et al., 2014).

Padua et al. (2012) investigated the association between the duration of a NMT program and alterations in movement pattern ability, and also reported a dosage effect. It concluded that the longer the athletes preformed NMT, the longer the prophylactic movement alteration the athletes retained. It is recommended that NMT sessions be practised frequently and for longer periods over a greater time span (Padua et al., 2012). Although numerous studies have been conducted and published on ACL injuries, and their potential risk factors and intervention programs to achieve effective risk-mitigation targets, an upward trend in NCACL injuries incidence is still being reported (Sugimoto et al., 2012,2016).

Clearly, to reduce the incidence of these devastating injuries (ACL injuries) in the high-risk female athletic population would be a multitasked offered. However, due to the fast nature of lifestyles, the high demand for achievement, and the high intensity of sports nowadays, there is a need for effective intervention programs. Most importantly, they need to be time-efficient and not interrupt the athlete's training time, yet achieve the volume and frequency needed to produce the desired prophylactic influences. That would mean more in-home practice programs but without the disadvantage of being complicated and difficult to do without supervision. One way in which this could be attempted is through perturbation training which has shown promising results in the literature.

2.7 Perturbation training and ACL injury risk reduction.

Several intervention programs that incorporate balance exercise besides other exercise elements reported trends toward reducing the risk for sustaining NCACL by improving its modifiable risk factors in female athletes who participated in intervention programs (Myklebust et al., 2003; Olsen et al., 2005; Petersen et al., 2005; Myer et al., 2006; Pasanen et al., 2008; Steffen et al., 2008; Lim et al., 2009; Cochrane et al., 2010; Kiani et al., 2010; LaBella et al., 2011; Walden et al., 2012; Letafatkar et al., 2015 ; Zebis et al., 2016). Balance exercise offers random perturbation with the potential to reduce the muscular reflex latencies, which could be considered as protective against high dynamic loads which encounter the knee joint ligaments during high intensity sport activities (Beard et al., 1994).

Perturbation training is a special type of neuromuscular training designed to enhance the development of dynamic knee stability (Fitzgerald et al., 2000; Cooper et al., 2005; Hurd et al., 2006). The significant changes identified in the muscle activation patterns after perturbation training suggest that motor-control strategies can modify and may benefit dynamic joint stability. Perturbation training appears to stimulate the afferent pathway, which provides information to the muscle spindle (Chmielewski et al., 2005). This improvement in sensitivity of the muscle spindles may result in enhancing the state of muscle readiness to respond to disruptive forces, which in turn would improve the knee dynamic stability (Hurd et al., 2006; Sell et al., 2007; Hart et al., 2010,2012; Letafatkar et al., 2015). Fitzgerald et al. (2000) demonstrated that incorporating perturbation tainting athletes who sustained primary ACL injury demonstrated result in a better return of functional activity in patients when compared with management with traditional rehabilitation programs. Key principle underlying the Perturbation training is that female should be exposed to carefully controlled forces that destabilize the knee joint enough to stimulate appropriate response without putting the knee joint at risk for future ligaments injury (Chmielewski et al., 2005). When skill acquisition and learning take place, rigid control over the degree of freedom is released in two stages; restriction are gradually lifted and the degrees of freedom become incorporated into larger functional unite (Chmielewski et al., 2005). In the second stage, the organization become more economical enhancing the efficiency of muscular force (Chmielewski et al., 2005).

Letafatkar and colleagues (2015) demonstrated that perturbation training exercises would result in significantly alteration the pattern of medial agonist-antagonist muscles surrounding the knee pre and post landing activity during SLL task. The study implemented NMT program on cohort of university female athletes with quadriceps dominance. Participants were introduced to perturbation training for 6 weeks 3 times a week on a progressive difficulty scale. The authors reported that participants performed the study NMT program which was focused on perturbation base training demonstrated that medial knee muscles VM-ST (VastusMedialis–Semitendinosus) co-contraction index in feedforward and feedback motor control phases had increased significantly from 20.55±1.31 to 25.93±1.45 %MVIC (maximal voluntary isometric contraction) at feedforward motor control phase and from 22.92±1.27 to 28.32±1.52 %MVIC at feedback motor control phase. On the other hand, the lateral knee muscles VL-BF (Vastus Lateralis –Biceps Femoris) also showed an increase in the co-contraction index from 22.33±1.19 to 29.10±2.57 %MVIC at feedforward motor control phase and from 46.73±2.27 to 54.66±3.77 %MVIC at feedback motor control phase. Furthermore, the study result demonstrate that Perturbation base training may altered the knee joint stabilization strategy from been joint stiffen pattern to pattern which may allow more dynamic stabilize at knee joint for female athletes, which may preserve the knee joint integrity overtime (Letafatkar et al., 2015). Perturbation training appears to stimulate the afferent pathway that provide information to the muscle spindle (Chmielewski et al., 2005). Thereby, the increase in muscle spindle sensitivity can result in better state of readiness of muscle to be more able to respond to disruptive torques. Thus, may assess in improving knee joint stability (Hart et al., 2010; Sell et al., 2007; Hurd et al., 2006).

Neuromuscular adaptation is characterised by an improvement in reactive “feedback” motor activation response to perturbation training, as prior experience of a perturbation leads to generation of proactive “feed-forward” motor responses that work in conjunction with reactive motor response to maintain posture stability (Wang et al., 2011). Neuromuscular adaptation in latency reflexes represents the effect of proactive muscle response that occurs when the motor system develops the ability to predict future motion and response accordingly based on previous motor experiences (Wang et al., 2011; Kumar et al., 2013).Feed forward motor responses represent the ability of neuromuscular control systems to use afferent “sensory” input to adjust the muscular recruitment pattern according to sensory input to predict the effect of mechanical disturbance in stability (Wang et al., 2011). Improved Feed-forward motor control and muscular pre-activation could be an underlying mechanism for fewer acute knee injury (Kubota et al., 2015). Feedback motor response occurs during or shortly after mechanical disturbance with the aim of restoring joint balance (Wang et al., 2011; Kumar et al 2013). However, changes in feedback muscle response that occur in the period of a long-latency reflex might be too slow to influence dynamic stability of the joint directly (Mandelbaum et al., 2005; Kubota et al., 2015).

Zebis et al. (2008) developed a NMT program with the main aim of enhancing neuromuscular control of the hip, knee, and ankle joint during athletic manoeuvers. The NMT program included exercise on balance mat and wobble board. The program had 6 levels each consisting of 3 exercises; each level had to be followed twice per week for 3 weeks before progressing to the next level. Each exercise lasted for around 20 minutes and was followed up every 2nd week. The main finding for the study was that program NMT may develop changes in the neuromuscular control activation pattern of the hamstring muscle during side cutting tasks. The results showed selective increases in medial hamstring muscle activity during the pre-landing and initial contact phases, which was parallel with unchanged neuromuscular activity of the quadriceps muscle. This represents important neuromuscular adaptations in response to the NMT used in the study, which would benefit female athletes with poor neuromuscular control, as it may reduce the risk of ACL injury. These findings are promising when considering the importance of having adequate neuromuscular activation of hamstring muscles when performing landing and cutting manoeuvers to enable the knee joint to withstand the high dynamic loads and protect the ACL (Zebis et al., 2008).

Zebis et al. (2016), conducted a study to observe the effect of balance and jump landing base intervention program on young female handball and football athletes. The intervention program was performing as part of the intervention group routine warm-up for 20 min a session 3 times a week for a period of 12 weeks. The authors reported alteration in hamstring to quadriceps muscular activation ratio at pre-landing a phase during side-cutting tasks. The outcomes agree with the outcomes reported by Zebis et al. (2008). This may demonstrate that prevention program might altered the pattern of agonist-antagonist muscle pre-activity during side cutting. This may represent a more ACL-protective motor strategy.

Wilderman et al. (2009) investigated the effect of 6 weeks' period agility exercise based intervention program. In accordance with studies by Zebis et al. (2008,2016) by funding increase medial hamstring activity during cutting tasks in young female basketball athletes. However, the increase in the medial hamstring muscle activity was observed at the contact phase of the cutting task and not in the pre-contact period as documented by Zebis et al. (2008, 2016). The difference in neuromuscular activity time respond may be related to differences in the nature of exercise used, as agility exercise applied by Widerman et al. (2009) primarily consisted of exercise focus on speed in shuffling the feet and changing direction, whereas, the studies by Zebis et al. (2008, 2016) and Letafatkar et al. (2015), interventions had emphasized more on postural balance exercise, balance in landing exercise and joint control during sports-specific exercise.

Restoring balance neuromuscular control between the medial and lateral thigh muscles in female athletes may reduce the peak knee valgus torques and angulation, which in turn may reduce the likelihood of ACL injury by reducing the strain on the ACL while performing sport activities (Cooper et al., 2005; Hewett et al., 2005 ; Myer et al., 2006).Therefore, employing NMT programs that incorporate balance and perturbation training could produce similar loads to those encountered in athletic activities. This may aid in the development of both feedforward and feedback motor activation strategies to establish sufficient activation to protect the ACL from high valgus loads during sports activities.

Unstable training devices such as wobble boards have demonstrated an ability to decrease musculoskeletal injuries in the lower limb in younger and older population. Several studies have demonstrated that balance training device such as wobble board or an unstable surface can improve knee and ankle muscles proprioception and strength during rehabilitation (Waddington et al., 2004; Waddington et al., 2000; Wester et al., 1996). In addition, it can help prevent lower limb injuries (Nigg et al., 2006; Myklebust et al., 2003; Wedderkopp et al., 1999; Caraffa et al., 1996). Interventions programs which incorporate proprioception and balance training utilized the principle that parts of the body act as a system of chained links lower limb muscles and joints, whereby, the whole limb is regarded as one kinetic functional unit starting from the foot proximately through the body segments (Haim et al., 2008; Zajec et al., 2002).

The effect of employing footwear in exercise program have more recently been studied in terms of neuromuscular adaptation. Gamada et al. (2013) studied the effect of footwear known as Realine Balance Shoes (RBS) (Figure 2-4) on female athlete participants in an exercise program.

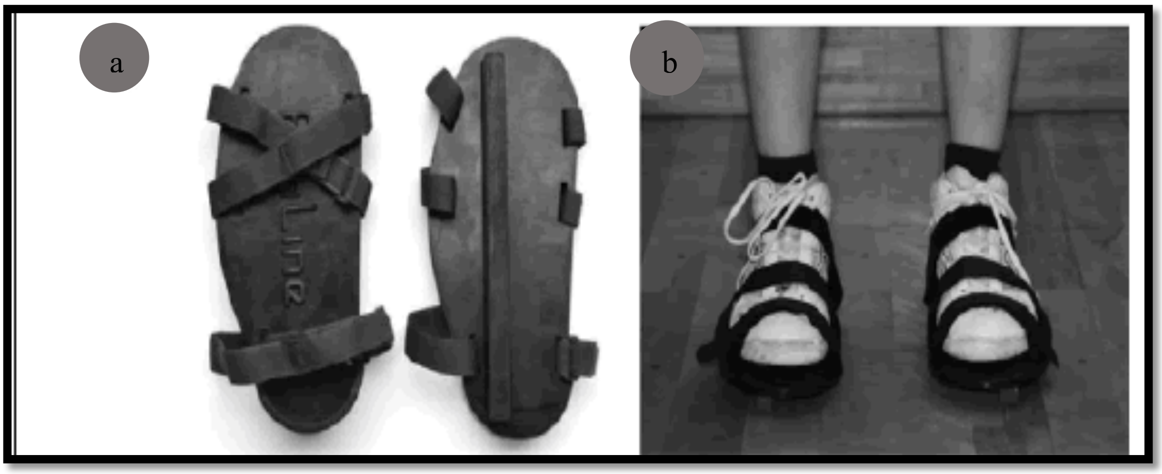


Figure 2- 4:Illustrate concept of the Realine Balance Shoes (GLAB Crop., Hiroshima, Japan) (Kubota et al., 2015).

The intervention involved 6 female athletes who participated in a 4-week exercise program, which was performed 3 times a week for 15 minutes each session. It included 4 stages of progressive intensity and difficulty. The participants in the study were instructed to keep the RBS sole horizontally balanced only while the knee-over-the-toe position was maintained, which challenged the dynamic stability of the lower limb with the aim of improving neuromuscular control. The program included joint realignment, balance training, close chain strengthening, and plyometric components (Gamada et al., 2013). The muscle activity of six lower limb muscles was recorded during DVJ and SLL functional tasks. The post-intervention EMG activity of medial hamstring: lateral hamstring ratio during the pre-landing and landing phase of single leg landing were higher than pre-intervention values (Gamada et al., 2013). The study demonstrates that the use of RBS during an exercise program would result in neuromuscular adaptation while executing landing maneuvers, which may reduce the risk of NCACL injury. However, the outcome of this study be taken with caution due several limitations to considered as there was no control group enrolled in the study and the authors did not assess the influence of the footwear on postural stability measures to evaluate if there were changes in postural sway amplitude or velocity which it would be mostly be in medial-lateral direction only (Gamada et al., 2013).

In a study by Kubota et al. (2015), conduct a RCT study to compare the effectiveness of an NMT program while wearing RBS (Realine Blanca shoes) and a conventional NMT prevention program, with the proposed to decrease lower limb injuries in particle ACL injury. The RBS intervention group used an unstable footwear device the RBS shoe (Figure 2-4), which is designed for correction DKV, while the control group used a modified version of intervention program previously used PEP (Mandelbaum et al., 2005). Each group performed their NMT program for 15 min, 3 times per week for 12 months. The RBS program aimed for correction dynamic knee valgus and included various type of exercise, such as Bilateral squat, knee bent walk, continuous jumping, single leg jump. The authors reported no ACL injury in the RBS group while there was one NCACL injury in female participates in the control group (Kubota et al., 2015).

Several unstable footwear has been developed during recent years, where they have produced favourable outcomes of functional activity and pain reduction (Farzadi et al., 2017; Apps et al., 2016; Price et al., 2013; Khoury et al., 2015). One proposed concept of footwear design was in unstable shoe construction, which aimed to induce controlled instability while standing and walking , for example by using balance pods centred in the fore foot and heel region (e.g., Reebok Easy Tone, ET) (Figure 2-5), or rocker-bottom (e.g., Masai Barafoot Technology, MBT) (Figure 2-6), which claim that those shoes designs had positive health affect in terms of increasing lower limb muscular activation during locomotion and /or decrease of joint loads (Horsak et al., 2015).

Figure 2- 5:Reebok Easy Tone,(www.Reebok.com).

The concept behind these designs is to introduce a controlled destabilisation which would challenge lower limb joint stability and balance control, this alteration in lower limb muscle recruitment pattern that may allow the user to develop motor control adequate to protect their lower extremity joint from potential hazardous loads during functional activities (Farzadi et al., 2017; Khoury et al., 2015). In a study by Landry et al. (2010), who investigated the effect of MBT (M. Walk model, Masai. Barefoot Technologies, Switzerland). The authors reported that postural sway did decrease between pre-past test visits for participant who used MBT unstable footwear only. This implies that lower limb muscular coordination may have been improved to reduce postural sway (Landry et al., 2010).

Figure 2- 6:Masai barefoot technology (MBT) (M-Walk.Masai Marketing & Trading AG).

Several research works document that incorporation of unstable footwear may induce positive biomechanical effects (Farzadi et al., 2017; Apps et al., 2016; Price et al., 2013; Stoggl et al., 2010). They demonstrated increase in lower limb muscle activity measures when using unstable footwear, which may have justified utilizing unstable footwear as a training method to improve lower limb muscle recruitment pattern and strength (Farzadi et al., 2017; Horsak et al., 2013; Demura et al., 2012). Each footwear design utilized different strategies such as, multi-density rocker sole and balance pods footwear, with the aim to impelling controlled instability to enhanced lower limb muscle activity during daily activity (Farzadi et al., 2017).

2.8 AposTherapy System.

The AposTherapy system (AposTherapy system, Apos –Medical and sports Technologies Ltd., Herzliya, Israel) (Figure 2-7). This biomechanical system (AposTherapy system) has shown the ability to manipulate knee jont alignment and subsequently muscular activation adjustmeant. The AposTherapy system showed promising result to address a number of different orthopaedic conditions such as knee osteoarthritis and low back pain which were the result of abnormal pathological movement patterns due to body mal-alignment, impaired neuromuscular control, and muscle weakness (Haim et al., 2008,2010; Bar-zir et al., 2010).

Figure 2- 7: AposTherapy footwear and its calibration mechanics (www.Apostherapy. co. uk). (Bar-zir et al., 2010; Haim et al., 2010).

The AposTherapy system is a biomechanical device in the form of a footwear which comprises of two modular elements attached onto each footwear platform (Haim et al., 2008). The elements are attached under the forefoot and hind foot regions of foot platform (Haim et al., 2008). Those biomechanical elements are convex shaped rubber elements, were each element can be individually calibrated (position, convexity, height, and resilience) to induce specific biomechanical challenges in multiple planes (Haim et al., 2008, 2010). The platform is equipped with a specially designed sole that consists of two mounting rails enabling flexible positioning of each element under each region (Haim et al., 2008, 2010).

Studies have documented that that control manipulation of the device element can significantly alter the foot centre of pressure (CoP) location (Khoury et al., 2015, 2013). The device has previously documented it can have an effect on the kinematic and kinetic parameters of gait for both knee osteoarthritis patient and healthy individuals (Khoury et al., 2015; Haim et al., 2011; Goryachev et al., 2011). The device demonstrated it is able to manipulate the knee and ankle sagittal moments by a controlled shift of the CoP sagittal plane (i.e., from posterior to anterior) and significantly correlated with knee extension and dorsiflexion torques during the stance phase (Haim et al., 2010). Furthermore, when the biomechanical elements were shifted on medial and lateral translation (i.e., medial to lateral) this significantly correlated with changes in the knee moments at the fronatal plane, where the external adduction moment (EKAM) could be reduced when the lateral coronal axis configuration was used (Haim et al., 2008) , The authors reported that an increase in EKAM was observed when the elements attached under the forefoot was in medial coronal axis configuration (Haim et al., 2008). Moreover, the convex shape of the elements puts the participants in a state of perturbation by every stap while while walking with device. Therefore, the neuromuscler adaptaion effect on lower limb msuclar activity pattern might be induce motor learning towards the desired neuromuscular gait pattern (Bar-Ziv et al., 2013).

The AposTherapy system has shown the capability to improve subjective and objective parameters in subjects with knee osteoarthritis (Haim et al., 2011). This been attributed to altering the biomechanical variables at the knee. Thus, reducing the frontal plane loads on the knee and associated significant pain reductions (Haim et al., 2011). The AposTherapy system have shown the ability to modify the activation of lower limb muscles in patients with knee osteoarthritis and healthy individuals as measured by electromyography (Haim et al., 2011, 2012; Goryachev et al., 2011).

The rationale behind employing of the AposTherapy system as the intervention for preventing NCACL injuries in high risk population, especially young recreational female athletes who have a high potential risk of sustaining primary-NCACL or/ and athletes who had primary-ACLR who have high risk of sustaining second NCACL at contralateral knee who are linked to insufficient neuromuscular control and higher risk movements patterns (Hewett et al., 2005; Paterno et al., 2010). This comes from the strong link between insufficient neuromuscular control and high-risk movements mechanics, which is documented to increase risk of primary NCACL injury in young female recreational athletes and /or second contralateral NCACL in young athlets who had ACLR (Ford et al., 2003; Hewett et al., 2005, 2009; Paterno et al., 2010, 2014). In addition, it is important to emphasis the flexibility in using the AposTherapy system could encourage its use as a more time efficient intervention component, yet brings the required neuromuscular control enhancement effect. That may establish incorporating the AposTherapy system as a promising addition to rehabilitations programs for post ACL reconstruction patients.

The idea of introducing the AposTherapy in rehabilitation program for post-ACLR patients, could also be an option as promising results has been reported while using the AposTherapy system in post-surgery rehab in THA (Total hip arthroplasty) (Bar-Zir et al., 2013). Evidence suggests that a second ACL injury risk could be as high as 30% or even more (Paterno et al., 2015; Leys et al., 2012; Hui et al., 2011) as neuromuscular imbalance and abnormal movement patterns could be observed years after ACLR and return to sports activities (Webster et al.,2016; Paterno et al., 2010, 2015). These neuromuscular deficits in lower limbs have been considered to be the main risk factor for second ACL injury (Paterno et al., 2010). Therefore, enhancing the neuromuscular control is believed to be important not just only to improve the functional recovery but also to reduce the risk for another ACL injury (Hart et al., 2017; Di Stasi et al., 2013).

Thus, it was logical to hypothesis that AposTherapy system could be a useful tool in intervention programs for preventing primary and secondary non-contact ACL injuries in female athlete and in athletes who had ACLR previously, and been identified to have imbalance in neuromuscular control (2D FPPA >8º) putting them at risk of injury.

2.9 Gap in the literature.

Until now no study has been carried out to investigate the possible effect of the AposTherapy system on lower limb biomechanical parameters, especially knee valgus angle and moment in recreational female athletes who have been identified to have a high risk for NCACL injury due to neuromuscular imbalance. Secondly, no study until now has investigated the effect of incorporating AposTherapy intervention in individuals who have had primary ACLR surgery and still show evidence of low neuromuscular control in their contralateral limb.

2.10 Research question and hypothesis.

The overriding research question is whether the use of the AposTherapy system in intervention will alter the lower limb biomechanical alignment following a six-week intervention program in recreactional female athletes and young individuals who previously sustain NCACL and had ACLR and return to sports activities with high risk movment patterns. It is hypothesized that the AposTherapy system will improve neuromuscular control and enhance the high risk biomechanical parameters related to risk of ACL injury (Knee valgus angle and moments) and muscular activity pattern of the lower limb in female recreational athletes and recreational athletes who had ACLR. This would reflect through visible reduction in their biomechanical and neuromuscular parameters, such as knee valgus motion and moments, improvement at the medial to lateral Q:H muscle co-contraction index activity, and their postural stability measures (CoP). Therefore, the specific null hypothesis are as follows:

- Hypothesis 1: There is a no significant difference in postural stability measures during single leg stance task, which would be reflected by no changes in the centre of pressure trajectory (CoP- excursion) before and after the AposTherapy intervention.

- Hypothesis 2: There is no a significant difference in maximum knee valgus angle during SLS and SLL tasks before and after the AposTherapy intervention.

- Hypothesis 3: There is no a significant difference in maximum knee valgus moments during SLS and SLL tasks before and after the AposTherapy intervention.

- Hypothesis 4: There is no a significant difference in muscle co-contraction of the medial side of the thigh (Vastus Medialis and Semitendinosus) during SLS and SLL tasks before and after the AposTherapy intervention.

- Hypothesis 5: There is no significant difference in muscle co-contraction of the lateral side of the thigh (Vastus Lateralis and Biceps Femoris) angle during SLS and SLL tasks before and after the AposTherapy intervention.

Chapter Three: General Methodology and Reliability

In this chapter, the biomechanical methods that were utilised in both two- and three-dimensional data capture, data processing and biomechanical modelling and computation will be discussed. Firstly, two-dimensional data capture and assessment will be discussed followed by the three-dimensional data capture and assessment. The test and retest reliability studies conducted will be presented followed the introduction of the biomechanical method in this chapter.

3.1 Two-dimensional motion analysis assessment and reliability.

3.1.1 Introduction.

Identification of high risk individuals enables risk mitigation programs to improve their effectiveness and be more efficient (Whittaker et al., 2017; Myer et al., 2007). One method that is widely utilized to identify individuals at high risk of musculoskeletal injury such as ACL injury are movement screening tests (Whittaker et al., 2017).Several screening methods have been reported in the literature to assess dynamic knee valgus, which included performing different tasks such as Single Leg Squat (SLS) (Willson et al., 2006; Willison and Davis, 2008; Mendonca et al., 2011), Single Leg Landing (SLL) (Herrington et al., 2010; Munro et al., 2012), Drop Vertical Jump (DVJ) (Munro et al., 2012), and Tuck Jump Test (TJT) (Hewett et al., 2005; Hewett et al., 2010; Letafatkar et al., 2015).

Most of the research work investigating lower limb and its relation to knee joint injuries have been incorporated by employment three-dimensional (3D) motion analysis to quantify biomechanics of the lower limb (Souza and Powers, 2009; Hewett et al., 2005; Ford et al., 2003). Assessment of lower limb kinematics during functional tasks may identify individuals who demonstrated abnormal movements mechanics that may lead to aetiology of exacerbation of knee joint injuries such as ACL injury (Munro et al., 2012; Jones et al., 2014: Gwynne and Curran,2014; Herrington et al., 2017). The usage of 3D motion analysis systems is considered the 'gold stander' method of quantifying multi-plane of lower limb joints alignment during functional tasks due to its high degree of reliability and accuracy (Ortiz et al. 2016; Willson and Davis, 2008). An alternative to 3D motion analysis is the use of 2D video analysis procedures where standard video cameras are used to capture performance of functional tasks which are then imported into software packages that perform kinematic analysis (Gwynne and Curran, 2014; Munro et al., 2012; Herrington et al., 2017). Therefore, 2D analysis may provide researchers and clinicians with a useful tool that is an inexpensive, portable and readily available (Mclean et al., 2005; Willson and Davis, 2008).

2D motion analysis has been used previously as a measurement tool to assess the dynamic valgus general athletics and injured populations (Willson et al., 2006; Willson and Davis, 2008; Munro et al., 2012). Willson et al. (2006) introduced the use of the Frontal Plane Projection Angle (FPPA) of the knee joint as a measure to screen for high risk individuals based on knee valgus motion during simple movement tasks, such as the single leg squat (Willson et al., 2006; Willson and Davis, 2008). The employment of 2D motion analysis for assessing 2D FPPA has been previously proved to have very good test-retest reliability within and between sessions (Munro et al., 2012; Dawson et al., 2015; Herrington et al., 2017), with quantitative measures showing excellent within-session reliability and good between-session reliability (Whatman et al., 2011; Munro et al., 2012; Dawson et al., 2015).

Several studies have been conducted to investigate the validity of 2D video analysis of movement mechanics patterns during functional tasks. (Herrington et al., 2017; Sorenson et al., 2015; Gwynn and Curran, 2014; Munro et al., 2012; Willson and Davis, 2008; Mclean et al., 2005). In a study by Mclean et al. (2005), demonstrated a relationship between 2D and 3D motion analyse in assessing frontal plane knee kinematics while performing side-jumping, side-stepping and shuttle run. The authors reported strong correlation (r=0.80 and 0.76, respectively) between peak 2D FPPA and 3D knee valgus angles for the side-jumping and side-stepping, respectively. However, the shuttle run showed lower correlation (r=0.2). Furthermore, Willson and Davis, (2008), found an association between the 2D FPPA and 3D hip adduction (r=0.32-0.38) and knee external rotation (r=0.48-0.55), during a SLS task concluding that the FPPA during SLS which are components of dynamic knee valgus.

In line with previous work demonstrating validity of 2D FPPA of the knee during single legged functional tasks. A recent study by Herrington et al. (2017), reported strong relationship between 2D FPPA and 3D knee valgus motion (r=0.79, p=0.008) during SLS. These outcomes were in line with work by Gwynne and Curran (2014) who reported 2D FPPA methods to be strongly correlated with 3D methods during SLS (r=0.78, p<0.001). Other studies reported a strong relationship between 2D FPPA and 3D knee valgus angle during single leg hop landing (r=0.72) (Sorenson et al., 2015) and during DVJ tasks (r=0.38, p<0.02 and r=0.59, p<0.001), for 3D knee valgus angle and moment, respectively (Mizner et al., 2012).

Several studies have proposed 2D motion analysis methods to screen for dynamic knee valgus (Willson and Davis, 2008; Ortiz et al., 2016 Herrington et al., 2017). The studies have recommended the 2D FPPA and the knee-to-ankle separation ratio (KASR) as a potential alternative instead of 3D motion analysis kinematic parameters for assessing dynamic knee valgus. In a study by Noyes et al. (2005), have reported that incorporation of normalized knee separation distance to quantify 'dynamic knee valgus'. Where in a study by Willson and Davis (2008), postulated that frontal plane projection angle (FPPA) to be more informative.

It is important to acknowledge that even though there is a strong relationship between 2D and 3D motion analysis in frontal plane knee angle. However, frontal plane 2D motion analysis has inherent limitation as it cannot measure kinematics that occurs in planes not perpendicular to the camera without potential for perspective error (Herrington et al., 2017). Perspective error is also known as parallax error is where something is not directly parallel with the recording device, which mean that it is being viewed from a different angle which could mislead any data that is obtained. As such motion capture may not be suitable for performance assessment of any motion that is not purely uniplanar such as the knee valgus motion at the knee, which in reality is a movement not only comprising of knee valgus and hip adduction in the frontal plane, but also hip internal rotation and tibial rotation in the frontal plane (Malfait et al., 2014). However, the work of McLean et al. (2005) confirmed this noting that 2D knee valgus angles were inherently influenced by hip and knee joint rotations.

It is logical to assume that 2D FPPA measures would have better association with knee valgus motion than knee valgus moments. This is likely because GRF is used to calculate moments that are not obtained in video analysis (Mizner et al., 2012). Furthermore, the type of functional task has shown to play a role in the level of association between 2D FPPA and 3D motion frontal plane motion. In a study by Herrington et al. (2017), the authors reported a strong correlation between 2D FPPA measurements and 3D knee valgus angle during SLS (r=0.79, p=0.008), whereas, a weak correlation (r=0.25, p0.37) was observed during SLL task for the same measurements. 2D FPPA measurements during SLS have strong criterion validity in some measurement of lower limb kinematics compared with the 3D motion analysis methods (Herrington et al., 2017). The differencesin validity between the SLS and

SLL might be due to the differences between the functional tasks and their impact on matching the exact moment of maximum knee flexion (Herrington et al., 2017).

One of the most common assessments undertaken with 2D motion analysis is performed during the single leg squat (SLS), which is considered as a simple, quick and cost effective task to analyse dynamic lower limb alignment (Willson et al., 2006). This has also been shown to provide useful insight into the assessment of knee joint alignment and the level of neuromuscular control during high load activities such as cutting and landing from running and jumps, without the need to subject the knee joint to higher loads associated with the type of sport activity (Alenezi et al., 2014; Gwynne and Curran, 2014; Munro et al., 2012; Whatman et al., 2011). Therefore, the purpose of this section is to determine the investigator's intra-ratter reliability in collecting 2D FPPA data from 2D motion analysis. This was established with a pre-post design to determine the between-session reliability, which was important as the screening of the individuals in the following intervention studies was by 2D analysis, and thus confidence in this measure was vital.

3.1.2 Method.

Participants: Nineteen physical active healthy participants Table 3-1, who were recreationally active male and female staff and students were recruited from the University of Salford via poster. All participants who are university staff and students have participated voluntarily. Previous reliability studies have recommended sample size between 15-20 participants (Atkinson and Nevill, 1998; Walter et al., 1998). This was achieved with the study sample population included 19 participants. Participants sports activities included Football (6), Netball (5), Basketball (3), Cheerleadry (1), and Volleyball (4).

All potential participants for the study were 18-39 years old, and considered active in recreational sports consisting of more than 30 minutes of physical activity three times per week regularly over the past 6 months. All subjects were required to be free from lower extremity injuries for the last three months and without a history of ACL injury or any chronic lower limb pathology or surgery. All participants also had a Beighton's score < 4 for general laxity. Participants were excluded from the study if they have history of neurological or systemic disorders, lower limb inequalities > 2 cm, or a history of any injury (which was defined as any musculoskeletal complaint which stopped the participant from undertaking their normal exercise routine for more than 6 weeks prior to the start of the study), or were already participating in injury prevention program. Ethical approval was acquired for the study from the University of Salford Research, Innovation and Academic Engagement Ethical Approval Panel (HSCR 13/69).

Table 3-1 2D Study sample characteristic.

Gender	Females (N=13) Mean ±SD	Males (N=6) Mean ±SD
Age (years)	24.4±5.4	27.7±5.9
Height (cm)	165.3±7.3	177.7±7.4
Mass (kg)	61±5.9	78.8±9.3

3.1.3 Procedures.

Upon arrival to human performance lab participants were briefed through the study and the objectives of the investigations, and the study equipment was explained to them as well. They were then asked to fill out and sign the informed consent form and complete the health history questionnaire which captured demographic information on the participants. Prior to the first session test, participants put on a comfortable t-shirt and a pair of shorts. Before each session participants were asked to warm-up on a stationary bicycle to ensure that all participants are doing the test while having same physiological status. Each individual was required to perform the SLS task where he/she would be assessed with 2D motion analysis.

Reflective markers were placed on the lower limbs of the participant to approximate the anatomical landmarks previously employed by Willson et al. (2006): at the centre of the ankle joint on the midpoint between the lateral and medial malleolus, at the centre of the knee joint on the midpoint between the knee latera and medial femoral condyles and another maker would be placed on the proximal thigh on the line from the anterior superior iliac spine to the knee centre marker.

A commercially available digital video camera (Exilim EX F1; Casio Corp, Dover, NJ) sampling at 30 fps was used. The camera was placed 60 cm above the floor level, 300 cm anterior to the participant's reference point on the med point of the force plate and was aligned perpendicular to the frontal plane (Herrington and Munro, 2010). Before any data collection, a calibration video was recorded for the triangular shaped calibration frame (Figure 3-1). The video calibration process was repeated if the camera had moved or if the participants changed his/her distance from the camera.

Figure 3- 1: Triangular Calibration frame.

Every participant was asked to perform three single leg squat (SLS) trials on each leg during each session. Data collection was collected on two different occasions separated by one week. The SLS task was performed by participants as described previously (Willson and Davis, 2008; Willson et al., 2006), with the investigator providing a demonstration of the squatting technique and providing standardised verbal instructions. Participants were instructed to stand on the test limb with the opposite limb flexed at the knee to approximately 45°. Each participant had their arms folded in front of their body to assist with balance and was looking straight head. Participants were instructed to perform SLS to 60° of knee flexion (Nguyen et al., 2011; Nakagawa et al., 2012b) in a controlled manner and without losing balance before returning to the stating position. Each squat was performed over a 5 second period at a standardized speed with the experimenter acting as a counter (Herrington et al., 2014; Alenezi et al., 2014). The 1st count initiated the movement, the 3rd count indicated the lowest point of the squat and the 5th indicated the end of the trial. Participants were given feedback on the depth of the squats (using a standard goniometer) and speed of their squat during these trials. In order to limit systematic bias each participant was requested to practice the SLS task until he/she felt comfortable with it; which usually took three to four trials until he/she was confident to perform the task correctly.

This all ensured standardisation of the approach for all participants. Trials were only accepted if the participant squatted to the minimum required degree of knee flexion and maintained balance throughout. To avoid any potential fatigue effect, a 30-second rest between each trial was given (Munro et al., 2012; Norcross et al., 2010). The selection of the starting side for the SLS task was randomly determined by asking the participant to choose one card from the two cards (one for right side and another for the left side). The card and the selected leg were the same followed throughout the follow-up assessment. All participants were asked to attend the human performance laboratory again one week later, where they repeated the same assessment. This allowed the assessment of the between-days reliability.

3.1.4 Data processing.

After the recording had been completed, the video footage was saved onto a PC in a password-protected file for later use. The video footage was uploaded to a Quintic biomechanics software package (version 26; Quintic consultancy Ltd, Sutton Coldfield, West Midlands, United Kingdom), which allowed the digitisation of the markers and the calculation of the FPPA of the knee (Figure 3-2). The average of the three trials per leg was used.

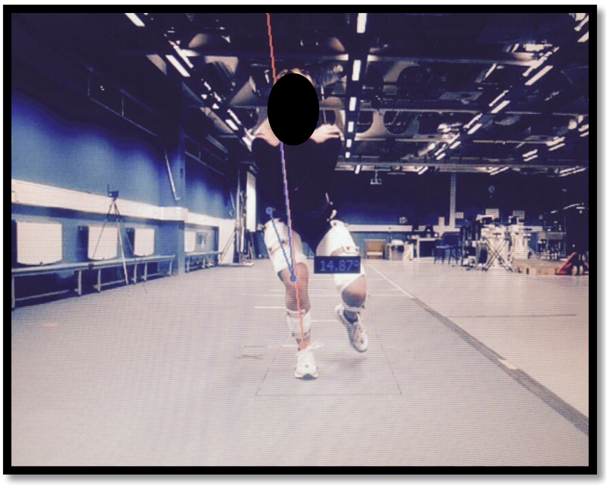


Figure 3-2: 2D FPPA Knee.

The FPPA of the knee was analysed on the digital frame corresponding with the maximal knee flexion point. The FPPA was measured during the maximum knee flexion angle during SLS. The maximum knee flexion angle was defined as the lowest point reached by the participant's pelvis during squatting. The analysis process started with uploading a calibration video, which was taken before the start of the participant's video recording. The calibration video was about 2 seconds of video recording for the calibration frame. Next, to be able to play the video in slow motion. After the software was ready to upload and to start analysing the recorded successful trials for the participants. The video was played until the maximum knee flexion frame was achieved for SLS tasks, while holding the video in the maximum knee flexion frame, the analysis began by drawing the lines between the markers. Starting from the ASIS to the midpoint of the knee joint, and other line from midpoint of the knee to the middle of the ankle mortise anatomical landmark to calculate the FPPA (Figure 3-2).

FPPA of the knee was measured as the angle subtended between the line from the marker on the proximal thigh to the midpoint of the knee joint and the line from the knee joint to the middle of the ankle mortise anatomical landmark (Willson and Davis, 2008; Munro et al., 2012). A measurement of 0 degree represent a natural postural of the frontal plane (Mizner et al.2012). The FPPA was defined as positive value when the knee joint moved towards the body midline (the knee markers were medial to the line between the ankle and thigh markers), while FPPA was defined as negative value when the knee marker was lateral to the body midline (Munro et al., 2012).

3.1.5 Data analysis.

The average of the three trials per limb per individual was used as the outcome for assessment. The relative reliability for 2D FPPA measurements was determined by calculating intraclass correlation coefficients (ICC) and 95% confidence intervals (CI) for between session reliability. The ICC provide an estimate of relative reliability for consistency of measurement and reflect the tests ability to differentiate between participants between sessions. However, the ICC does not provide information about the accuracy of individual scores. ICC values were interpreted according to criteria outlined by Coppieters et al. (2002) (Table 3-2): poor < 0.4, fair 0.4-0.7, good 0.7-0.9 and excellent > 0.9. All statistical analysis was conducted using SPSS (Version 26.0. IBM SPSS Statistics, USA).

The absolute reliability for 2D FPPA measurements was determined by calculating measurement error scores were established by calculating the standard error of measurement (SEM). The SEM provides a value for random measurement error in the same unit as the measurement itself and reflects the degree to which repeated measurements vary from individuals for any test occasion (between session reliability) (Koo et al., 2016). The minimum detectable difference (MDD), was calculated to establish the minimum changed to be considered practically significant (Kropmans et al., 1999). The standard error of measurement SEM is a measure of absolute reliability that can be used to enhance clinical decision making by quantifying the reliability of 2D FPPA scores within individual's participants on different occasions (Stratford et al., 2004). SEM can communicate measurement error associated with 2D FPPA video analysis in clinically useful terms as it is expressed in the same units as the original measure (Koo et al., 2016).

The test-retest reliability indicates the reproducibility of the observed value when the test is repeated (Hopkins et al., 2000). The drawback of ICC is the lack of information regarding the actual difference between measures and its sensitivity to sample heterogeneity (Atkinson and Nevill, 1998). A low standard error of measurement (SEM) with high ICC indicates good reliability of a measure. Therefore, SEM and the minimum detectable difference (MDD) were used in conjunction with ICC and a CI of 95%. Intra-class correlation (ICC) model used to assess relative reliability (model 3,k), were the first number point out the use of the two-way mixed model of ICC, whereas the second number would represent the use of an average measurement (Portney and Watkins,2009; Koo et al., 2016).

Table 3 -2: ICC values and corresponding levels.

ICC value	Interpretation
Less than 0.40	Poor
0.40-0.70	Fair
0.70-0.90	Good
More than 0.90	Excellent

The SEM was calculated for all variables using formula SEM=SD (pooled) × (√1-ICC) (Thomas et al., 2005). The MDD according to Denegar and Ball, (1993), genuine changes can be discrimination from erroneous measurements by using the SEM. Nevertheless, Atkinson and Nevill (1998) and Thomas et al. (2005) noted that as little as 68% of all test scores comes within one SEM of the correct score, in contrast to the frequently employed bench mark of 95%. Therefore, the MDD statistic has been used to determine the amount of change needed to signify statistical changes (Atkinson and Nevill, 1998; Eliasziw et al., 1994). It has been known as the minimum value that should be exceeded to distinguish between random error in measurement and a real change in performance score (Atkinson et al., 1998; Eliasziw et al., 1994). The MDD was calculated according to the formula cited by Kropmans et al. (1999), MDD =1.96 x (√2) x SEM. Both SEM & MDD are expressed in the units of the measurement tool used (degrees for joints angles) (Blankevoort, et al., 2013).

3.1.6 Results.

Table 3-3 shows the combined data for between- session reliability for all the participants ICCs, SEM and Mean. The 2D FPPA measures for the right knee during SLS showed good between-session (ICC = 0.89, 95%CI = 0.70 - 0.96) reliability, along with 2D FPPA for the left knee, which also demonstrated good between-session (ICC=0.88, 95%CI=0.68-0.96) reliability. The SEM for this study was very low which gives more confidence to the finding of the results using the 2D video analysis (1.12-1.33°) Table 3-3.

Table 3-3: Between-days ICC, Mean, SEM and MDD values for 2D FPPA knee variables during SIS task for (n=19) participants.

Variables	**ICC (95%CI)**	**Mean (SEM) (°)**	**SEM% of Mean**	**MDD (°)**	**MDD% of Mean**
FPPAK (Right)	0.89 (0.70-0.96)	11.15 (1.12)	10.04%	3.10	27.80%
FPPAK (Left)	0.88 (0.68-0.96)	11.86(1.33)	11.21%	3.55	29.92%

FPPAK (Frontal Plane Projection Angle of the knee); ICC (intraclass correlation coefficients); SEM (standard error of measurement); MDD (minimum detectable difference).

3.1.7 Discussion.

The aim of this study was to establish the between-session reliability and measurement error of 2D FPPA for the knee during the SLS task. This analysis has shown that for the individuals assessed in this study, the investigator measurement of FPPA can be considered a reliable measurement outcome, with the 2D FPPA analysis to be used as a practical screening tool to identify potential participants with high knee valgus motion.

The present study showed that 2D FPPA SLS task is reliable between days. In line with previous work (Herrington et al., 2017; Dawson et al., 2015; Gwynne and Curran, 2014; Munro et al., 2012) 2D FPPA assessment was shown to be reliable between-days for SLS task. In study by Munro et al (2012) reported good 2D FPPA ICC values 0.72-0.82, while in Gwynne and Curran, (2014) it also reported good 2D ICC of 0.74. Excellent reliability scores of 0.93 reported by Dawson et al. (2015) while in Herrington et al. (2017) it was 0.87, which is comparable to the current study outcomes shown in Table 3-1, which were 0.89 for right knee and 0.88 for the left. Generally, the standard error measurement in the current study was slightly less than those reported by Murno et al. (2012), which ranged between 2.72° and 3°, Gwynn and Curran (2014) with SEM scores ranged between 2° and 3.8° and study by Dawson et al. (2015) with SEM values reported 3.01. Nonetheless, it was lower from the SEM values reported by Herrington et al. (2017) of 1.93°. The finding of the present study along with those of Herrington et al. (2017), Gwynn and Curran (2014) and Munro et al. (2012), indicate that the methods used are sufficiently robust to provide reliable results across testers and time points, which open the possibility of using these tests in multi-centre trials.

Good between-session reliability scores, coupled with low SEM values, indicate that there is minimal investigator error in relation to overall measurement error, and that any error above the study SEM values is due to systematic bias or random error (Alenezi et al., 2014; Munro et al., 2012). A number of factors can influence the reliability of a test. These can be broadly grouped into systemic bias and random error. Systematic bias refers to a trend for measures to be different as the result of fatigue or a learning effect (Cortes et al., 2011; Beaulieu et al., 2008). In this study, this was limited as participants were asked to perform practice trials to familiarise them with the task, and a sufficient rest period was allowed to avoid any influence of fatigue. In addition, the order of which side the task was started was also randomised. Whilst, random error is the noise in measurement typically seen as within-subject variation, inconsistencies in the measurement protocol or the examiner measurements (Hopkins et al., 2000; Tyson et al., 2007).

Several factors influence between-session reliability, such as skin marker movement, referenced static alignment, and task difficulty (Ferber et al., 2002; Ford et al., 2007). Kadaba et al. (1989) attributed the variability of between-session measures to marker reapplication whereas in this study only one investigator with 14-year clinical experience attached the markers in all trials and to all participants. The majority of studies investigating knee valgus and its relation with knee injury have employed the use of 3D motion analysis to assess their kinematics (Ford et al., 2003; Hewett et al., 2005; Souza and Powers, 2009). However, several studies have used 2D FPPA to assess dynamic knee valgus during common functional tasks in athletic and general populations (Willson et al., 2006; Willson and Davis, 2008; Herrington and Munro, 2010; Munro et al., 2012; Mendonca et al., 2011; Herrington et al., 2014; Dawson et al., 2015). Female athletes demonstrated high 2D FPPA when compared with male athletes during the drop vertical jump (DVJ) and SLS tasks, which is a similar finding to the 3D studies (Willson et al., 2006; Herrington and Munro, 2010). Furthermore, 2D PFFA was sensitive to changes in dynamic knee valgus, which resulted from intervention training or injury (Dawson et al., 2015; Herrington et al., 2014).

The currant gold standard method for investigating kinematic and kinetic of lower limb is by using 3D motion analysis and force platforms (Mizner et al. 2012; Gwynne and Curran, 2014). However, the employment of 2D FPPA measurement to analyse the dynamic knee valgus has several advantages over 3D measurement in terms of equipment cost and time efficiency regarding the time to collect and analyse the data (Willson and Davis, 2008; Herrington et al., 2010; Munro et al., 2012). Nonetheless, in a study by Willson and Davis. (2008) have documented that 2D FPPA was significantly correlated to hip adduction and knee external rotation of 3D kinematic measures during performing SLS task. The hip adduction and knee external rotation is considered two of components of the dynamic knee valgus (Hewett et al., 2005). Nonetheless, as previously mentioned it has been documented in literature a considerable level of assossiation between 2D FPPA measures and 3D dynamic knee valgus during varies functional tasks (Mizner et al., 2012; Munro et al., 2012; Gwynne and Curran, 2014; Sorenson et al., 2015; Herrington et al., 2017). Thus, the employment of 2D analysis for assessing dynamic knee valgus might be useful for screening and identifying individuals with high risk measures for NCACL injury (Munro et al., 2012).

Even though the relationship between 2D FPPA measures and 3D knee frontal plane kinematics have not been explored in the current study. However, there is growing evidence demonstrating the strong relationship between 2D FPPA and 3D knee valgus motion during SLS functional task (Munro et al., 2012; Gwynne and Curran, 2014; Herrington et al., 2017). In addition, studies demonstrated an acceptable level of inter-rater relibiltiy for experienced physiotherapists and clinicians (Kennedy et al., 2010). A good to excellent level of inter-rater reliability been documented for multiple-ratters when observing 2D FPPA during SLS of ICC=0.89 (Mizner et al., 2012) and ICC=0.97 (Herrington et al, 2017).

The single leg squat SLS has been used as a qualitative measure to evaluate lower limb injury risk (Kennedy et al., 2010). While SLS is considered a simple low impact task, yet, it can identify unilateral mechanical movement dysfunctions (Weeks et al., 2012). 2D FPPA measurements were found to have strong correlation with 3D knee valgus angle (r=0.79, p=0.008) during SLS task but not in SLL (r=0.21 p=0.8). 2D FPPA measurements during SLS have strong criterion validity in some measurement of lower limb kinematics compared with the 3D motion analysis methods (Herrington et al., 2017). The difference in validity between the SLS and SLL might be due to the difference between the functional tasks and their impact on matching the exact moment of maximum knee flexion angle. 2D FPPA is captured at the point of maximum knee flexion. However, because of the different capture speeds between 2D video and 3D motion analysis, during the high-speed task of SLL. The poor correlation could relate to an inability to measure at exactly the same knee flexion point. In contrast, during the slower task of SLS it is more likely that the 2D video and 3D motion analysis to be more associated (Herrington et al., 2017).

This study outcome has limited generalisability as the relationship were only observed in healthy uninjured recreational athletes and future studies is required to identify if these or different relationship occur in individuals with musculoskeletal disorders such as individuals post ACL injury. In addition, the present study only assessed intra-ratter reliability.

3.1.8 Conclusion.

The reliability and measurement of error of 2D FPPA have shown good levels of reliability and low measurements error in this study. It has been shown in this section that the collection and analysis of 2D FPPA during the single leg squat is a reliable tool to provide a gross measurement of lower limb kinematics in the absence of 3D kinematic measures, and that studies could employ this measurement method to screen participant’s lower limb kinematics.Therefore, 2D FPPA of knee joint will be used in the screening of individuals in order to identified individuals with potential high risk of sustaining NCACL injury in the different studies that will be presented throughout this thesis.

This study outcome has limited generalisability as the relationship were only observed in healthy uninjured recreational athletes and future studies is required to identify if these or different relationship occur in individuals with musculoskeletal disorders such as indivdauals post ACL injury. In addition, the present study only assessed intra-rater reliability.

3.2 Three-dimensional (3D) motion analysis, electromyography (EMG) analysis and CoP-Excursion assessment and reliability.

As discussed in the previous section, 2D motion analysis is a useful technique for a quick, simple and easy assessment of the kinematics of the lower limbs and in particular, the FPPA of knee joint. However, 3D motion analysis is still considered the gold standard measurement of kinematics and kinetic measures of lower limb. Thereby, it would be utilised in studies curried in this thesis. Nevertheless, surface electromyography analysis will be used to assess the muscle work pattern of lower limb during the study functional tasks. In addition, centre of pressure measures trajectories sway would be utilised to evaluate the changes in posture stability. Therefore, the following sections will cover the different aspects reliability of 3D, EMG and CoP-Excursion data collection.

3.2.1 Introduction.

Reliability is a vital indicator of the extent to which the results of scientific studies can be reproduced in subsequent testing (Batterham and George, 2003). Thereby, proper comprehension outcome measurements of the reliability and measurement error associated with 3D analysis is essential.

The 3D motion analysis is considered to be the gold standard for motion analysis, as it allows to quantify all movement components in all three planes during dynamic assessment (Schurr et al., 2017; Meldrum et al., 2014; Munro et al., 2012). By placement of reflective markers on the body specific anatomical landmarks, the skeletal system can be recreated while biomechanical features can be measured and recorded during difference functional tasks. Therefore, the reliability of different motion measurement instruments (2D, 3D) is largely dependent on the placement of markers between sessions; several studies have reported that errors in the placement of markers could significantly impact the reliability between sessions (Ford et al., 2007; Queen et al., 2006). In addition, skin movement artefacts could also affect measurement accuracy (Cappozzo et al., 1995, 1996).

In a study by Kadaba et al. (1989), which was considered to be one of the first investigations into the reliability of quantitative motion analysis, it was reported that the reliability of kinematic and kinetic variable measurements within the same session were higher than that observed in different sessions. Specifically, this trend has been demonstrated in drop vertical landing (Ford et al., 2007), stop-jump landing (Milner et al., 2011), single leg squat and single leg landing (Alenezi et al., 2014) and pivoting (Webster et al., 2014). Biomechanical studies have demonstrated differences in the degree of reliability between certain motion planes. Motion in coronal and transverse planes seems to be more influenced by error in the placement of markers than that in sagittal planes (Kadaba et al., 1989), which have demonstrated higher stability across measurements during single leg landing walking, running, and drop vertical jumps (Alenezi et al., 2014; Milner et al., 2011; Ford et al., 2007; Ferber et al., 2002; Kadaba et al., 1989).

The use of surface electromyography (surface EMG) has been considered a useful non-invasive method which allows a direct assessment to the muscle activities by providing information on muscle activation patterns and/or degrees of activation; this can be performed through identification of the electrical potential resulting from muscle contraction by using surface EMG (Chowdhury et al., 2013; Farina, et al., 2010; 2014). Researchers can, thus, employ surface EMG to provide detailed magnitude of muscle activation and onset timing, as well as to illustrate motor unit recruitment patterns and coordination strategies during different functional tasks and rehabilitation exercise (Arokoski et al., 2004; Santilli et al., 2005; Norcross et al., 2010; Sakamoto et al., 2009). Moreover, this technique could also improve the understanding of muscle recruitment patterns during certain dynamic tasks. Consequently, several studies have used surface EMG to provide data on muscle recruitment patterns and the magnitude of muscle activity during certain periods of gait or tasks. Thus, it could help to investigate biomechanical risk pattern or access the effect of intervention on muscle group or certain muscle after NMT (Letafatkter, et al., 2015; Norcross et al., 2010; Palmieri-Smith, 2009). Joint stiffness can be dynamically regulated by adjustment in muscle activity intensity (Silva et al., 2009). The simultaneous activation of the muscles surrounding the joint (co-contraction) may increase the joint stiffness resulting in enhancing the ability to resist external loads (Fonseca et al., 2004).

The identifying of an actual surface EMG signal that originates in the muscle could be lost as a aresult of the mixing of various noise signals or artifacts (Chowdhury et al., 2013). The extrinsic factors like the electrode positioning and configuration are controllable. However, intrinsic physiological factors like individual skin formation, blood flow velocity within the muscles, the thickness of the subcutaneous tissue, muscle fibre type and diameter cannot be controlled (Mogk et al., 2003; Chowdhury et al., 2013). This could result in cross-talk from other muscles which may contaminate EMG signal. Hence, cause an incorrect interpretation of the signal information (Farina et al., 2004). Therefore, it is essential to carefully choose the electrode size and inter-electrode distances (Winter et al., 1994). In addition, important to normalise the EMG signal amplitude to obtain a standard value when comparing between different participants, muscles functions while conducting repeated measures across difference assessment sessions (Fernandez-Pena, 2009; Norcross et al., 2010). The EMG data amplitude is usually normalised to a maximum voluntary isometric contraction (MVIC) (Mohr et al., 2017; Letafatkter, et al., 2015; Palmieri-Smith, 2009). The data normalisation procedure is designed to investigate the extent to which the muscle is active during a task, in terms of its maximum static and dynamic activation capacity (Burden, et al., 2003).

In the published literature it appears a variety MVIC methods have been used to collect MVIC data, as can be observed in the range of MVIC test positions applied to the subjects, the varying test intensities, and the different fixation methods undertaken (Bolgla and Uhl, 2007; Norcross et al., 2010; Burden et al., 2010). In this study, in order to limit this conflation, we endeavored to follow the method adopted in studies similar to our own in terms of muscle location and types of sample population tasks and nature of intervention in an effort to obtain the best possible base of comparing our study with other studies (Palmieri-Smith, 2008, 2009; Letafatkter, et al., 2015).

Because of the design of the human body it is inherently unstable, hence a postural-control system is required in order to preserve an upright stance (Palmieri et al., 2002). Nonetheless, postural-control system involves a complex multimodal interaction between musculoskeletal and neural system (Shumway-Cook et al., 2012; Winter et al., 1995). Postural control consists of two components including postural stability and postural orientation (Lehmann et al., 2017). Postural stability to a large extent assimilate somatosensory information to control the centre of mass (COM) in relationship to the base of support (Shumway-Cook et al., 2012). While, postural orientation, defined as the ability to stabilize body segment in relation to each other and to the environment during a static or dynamic task (Nae et al., 2017; Horak et al., 2005). Postural orientation is reflected by kinematic outcomes that can be measured by clinical observation or motion-analysis technology such as 2D and/ or 3D motion analysis techniques. Knee joint position, in particular knee valgus motion is commonly assessed as a measure of postural orientation (Nae et al., 2017).

It has been documented the use of CoP measures to be considered useful tool to evaluate postural stability (Lehmann et al., 2017; Kouvelioti et al., 2015). Thereby, CoP measures is considered to be a helpful procedure for physicians and physiotherapist to identify individuals with potential risk for sustaining ACL injury (Lehmann et al., 2017; Farzadi et al. 2017). Several studies have incorporated CoP measures in terms of an amplitude or velocity during single leg stance with eye open to evaluate postural control (Negahban et al., 2014; Price et al., 2013; Okuda et al., 2005; Ageberg et al., 2005).

The movement of the CoP trajectories varies depending on the movement of the COM, and it also depends on the projection of the muscle forces required to control or produce movements (Palmieri et al., 2002; Hsu et al., 2007; Ko et al., 2013). The CoP- trajectories range of movement, is an average value overall data point collected in a trial and is a more representative measure of postural stability. Increase in average CoP range of movement suggest reduction in postural control, whereas a reduction in thought to represent increase postural stability (Browne et al., 2000; Baloh et al., 1998). The area of sway outlines the total area covered by the CoP in both A/P and M/L direction (Lehmann et al., 2017). The objective of this current study was to quantify postural stability during single leg stance in healthy control subjects.

Multidisciplinary approaches are typically employed with the aim of recognising potential movement patterns that underlie increasing risk of musculoskeletal injuries. Therefore, the assessment of athlete's performance and injury risk parameters have been the focus of sport medicine studies and research (Secrist et al., 2016; Stevenson et al., 2015; LaBella et al., 2014; Myer et al., 2010). It is necessary to gain a full appreciation and understanding of the day-to-day variables, especially when observing treatment effects or responses over time (Monajati et al., 2016; Myer et al., 2013; Sugimoto et al., 2012). Therefore, the aim of this study was to investigate test and re-test reliability of using 3D motion, surface EMG analysis to measure lower extremity kinematic and kinetic variables, during single-leg landing and single-leg squat and CoP-Excursion during Single Leg Stance.

3.2.2 Method.

3.2.2.1 Participants.

Eleven recreationally active male and female staff and students were recruited from the University of Salford via poster. The sample size of the study was considered appropriate with the study by Wimmer and Dominick (2003), recommended that the sample size of the reliability studies should be between 10% and 15% of the main study sample size, which was estimated to be 33 in each of three study groups using G power software (Faul et al., 2009,2007). The main study sample size would be 99 participants. Therefore, the reliability study sample size will be 10%-15% (10-15 participants) of the main study sample size. Participants sports activities included Football (6), Netball (3), Rowing (1) and Basketball (1).

The inclusion criteria for the study population required that all potential recruits for the studies were aged 18-39 years old, and they were considered active in recreational sports consisting of more than 30 minutes of physical activity three times per week regularly over the past 6 months (Dawson et al., 2015). All subjects were required to be free from lower extremity injuries for the last three months and without a history of ACL injury or any chronic lower limb pathology or surgery. All participants also had to have a Beighton score < 4 for general laxity. Participants were excluded from the study if they had a history of neurological or systemic disorders, lower limb inequalities > 2 cm, or a history of any injury that could be defined as a musculoskeletal complaint which stopped the participant from undertaking their normal exercise routine for more than 6 weeks prior to the start of the study. Participants were also excluded if they were already participating in another injury prevention program. Prior to testing, each participant read and signed a written consent form that had been approved by the Research Ethical Approval Panel at the University of Salford (HSCR 13/69).

All participants were initially tested twice on their first visit (two sessions), with approximately one-hour gap between the sessions to investigate within-day consistency, then after period of one week participants were retested again with one session in similar way as the initial test to assess the between-day reliability.

3.2.3 Procedures.

3.2.3.1 Three-Dimensional (3D) motion analysis.

Instrumentation

The size of the capture volume is important as this affects to data accuracy and quality. Therefore, an appropriate camera position is essential to have the optimum capture volume in the camera field of view (Figure 3-3) (Richards et al., 2008; Pantano et al., 2005). The most suitable camera position is the one that minimises the blind space surrounding the chosen capture volume for the field of view of the cameras (Richards et al., 2008; Alenezi et al., 2014). Ten infrared (IR) cameras (Oqus 7, Qualisys AB, Sweden) were located around three force platforms in an umbrella configuration sufficient for the collection of the movement of research variables of interest during performing the functional tasks of the research: single leg squat, single leg landing and Single Leg Stance tasks. The collection of kinematic and kinetic data of the lower extremity was managed in a biomechanical laboratory which also has three force platforms (AMTI BP 600900, Advanced Mechanical Technology, Inc., USA). The motion analysis system sampled at 250 H_z, force platforms sampled at 1500 H_Z, and the EMG system sampled at 3000Hz were all synchronised together.

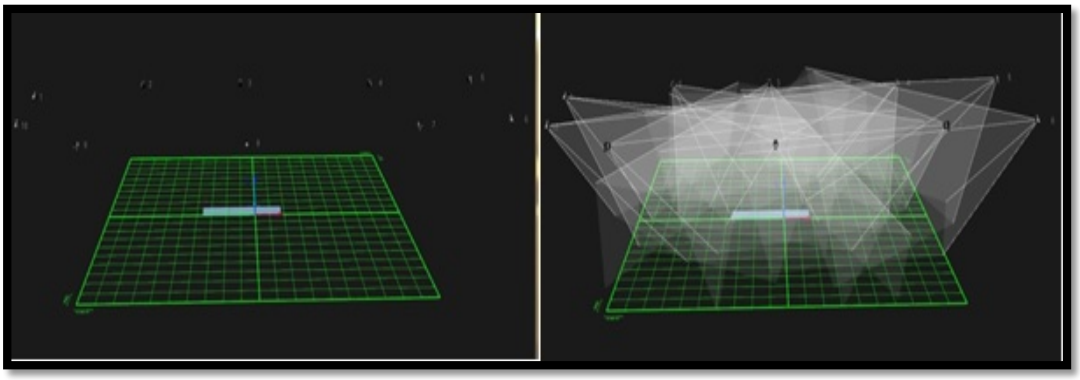


Figure 3- 3:Layout of the capture volume.

System Calibration

For the marker coordinate data to be captured, the IR cameras produce a 2D image which will then be converted into a 3D workplace so the marker position would be 3D coordinated in a global reference coordinate system using a direct linear transformation technique (Richards et al., 2008; Alenezi et al., 2014). The accuracy of the marker position in 3D space is determined by the calibrated system (Payton and Bartlett 2008). A lower measurement residual reflects a higher accuracy of 3D marker location. As measurement residuals are usually accepted below 1.00 mm. To set the origin of the coordinative system of the laboratory (Global System), a rigid L–shaped metal frame with four reflective markers attached to it (Figure 3-4a), was placed on the corner of the first force platforms parallel to its X and Y axes with a predefined distance between the markers and the origin of the force platform coordinate system, which were automatically calculated and inputted into the software (Winter et al., 2009).

A handheld wand with two reflective markers at a distance of 601.7mm (Figure 3-4b) was used to ensure the capture volume to be calibrated. A capture time of 45 seconds was set for the calibration. In order to achieve a well-calibrated system, it was important to wave the wand in the entire workspace that included the low and high floor level were best covered so at least two cameras could observe the wand movement, while the L shaped frame was still on the force platform to determine the orientation and position of the 10 cameras relative to the laboratory coordinate system (Payton and Bartlett 2008; Richards et al., 2008).

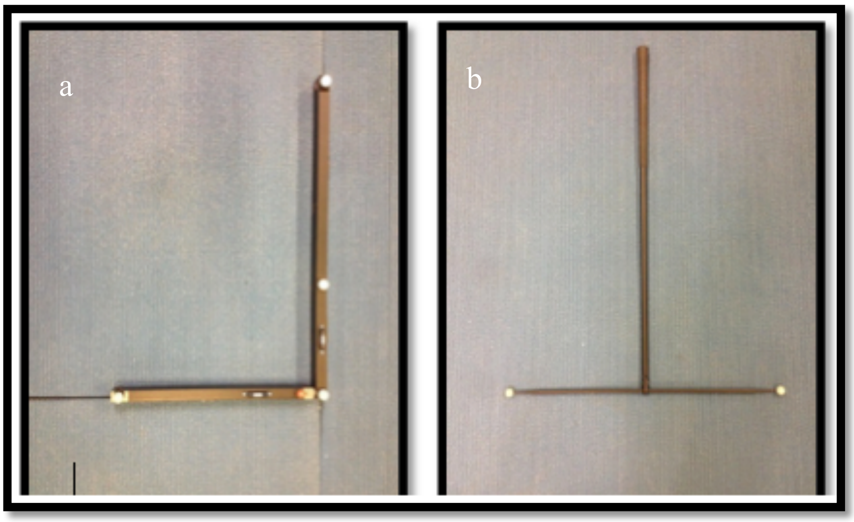


Figure 3- 4:Calibration tools. a. the L frame, b. the handheld Wand

Marker Placement

Reflective markers which was 14.5 mm in diameter with flat base (Figure 3-5) were used on each participant for each testing session, and hypoallergenic double-sided adhesive tape was used to attach the markers to the participant's skin. During capture time it's essential for each marker to be capture by at least two cameras at any instant (Payton and Bartlett, 2008). Moreover, the position and orientation in 3D space to be defined, the markers could not be in a straight line for segment to be defined, it acquired the use of three non-co-liner markers was suggested (Cappozzo et al., 1995). The calibration anatomical system technique (CAST) was employed to determine the motion of each segment and anatomical significance during the dynamic trials (Cappozzo et al., 1996). CAST, when compared with the modified Helen Hayes marker set, would offer advantages of enhanced anatomical relevance (Kadaba et al., 1989).

Figure 3- 5:The 3D motion system markers, clusters set-up for thigh and leg.

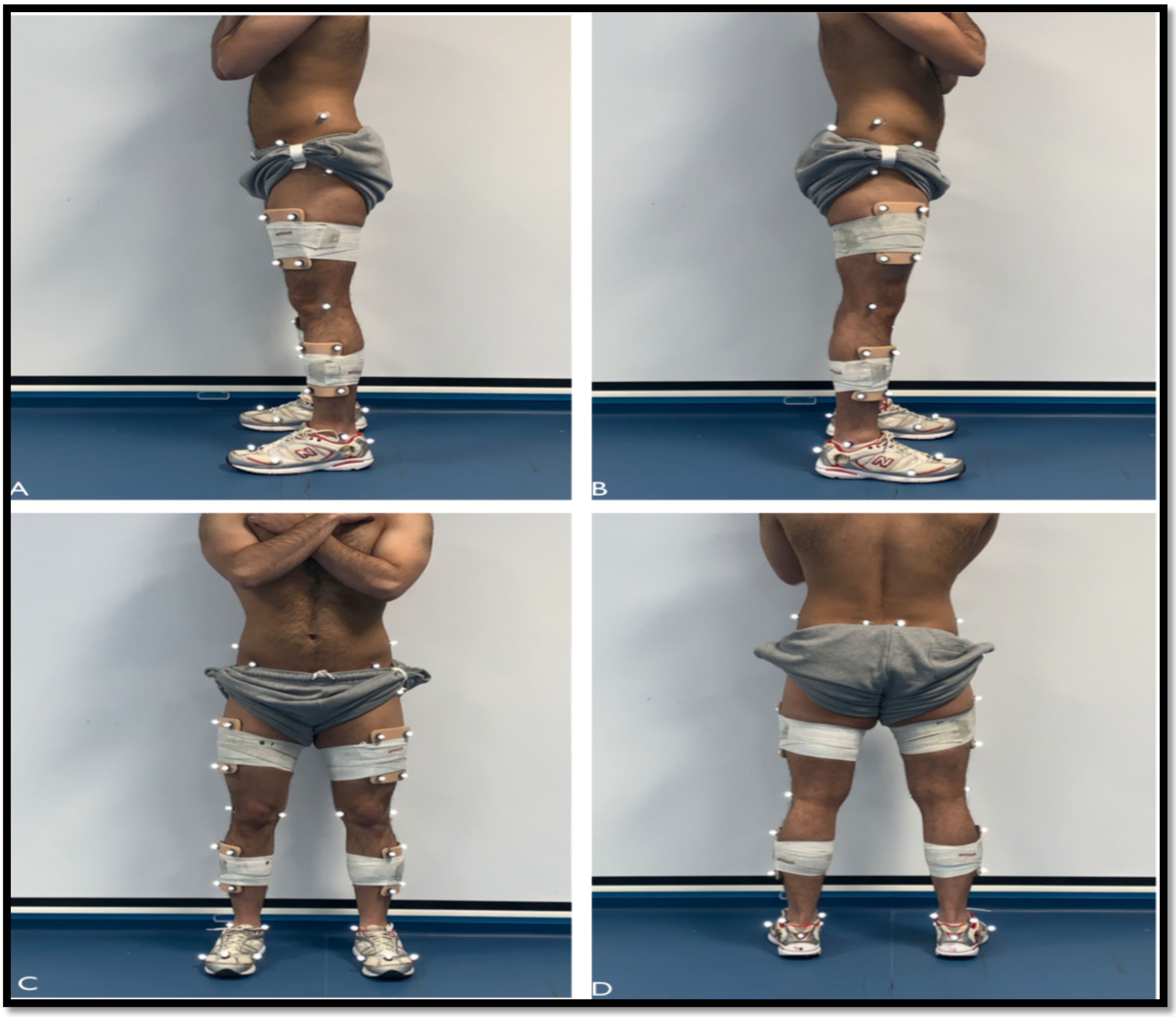


Figure 3- 6: Marker set-up with anatomical and rigid markers clusters in place. a and b Lateral view, c Anterior view and d. Posterior view.

A total of forty markers (anatomical and track markers) were placed on each participant to define the anatomical reference frame and centres of joints rotations (Figure 3-6a-d). The markers were attached on anatomical landmarks at the distal and proximal ends of the segment and at the lateral and medial aspects of the joints. Markers were placed at the following anatomical landmarks: pelvic markers were attached to the left and right anterior superior iliac spine (ASIS), the left and right posterior superior iliac spine (PSIS), and the right and left iliac crest. In addition, the thigh markers were attached to the greater trochanter, the knee markers were attached to the lateral and medial femoral condyles, the ankle markers were attached to the lateral and medial malleolus and finally foot markers (on the 1st, 2nd, 5th metatarsal heads and Calcaneal tubercle).

Following a satisfactory capture of the static markers, all the anatomical markers were removed, only 28 tracking markers kept on (8 markers on both lab shoes, 4 markers on the pelvis at ASIS and PSIS, and 16 markers over 4-cluster plates). The four clusters (Figure 3-5) used in current study were positioned at the anterior lateral aspects of both thighs and legs (Figure 3-6 a-d), and they were attached by using double-sided adhesive tape with crepe bandages (Fabriofoam, USA, 5cm x 2m) to avoid any movement of the cluster plates during the dynamic trials. The use of rigid clusters has been suggested to offer a better configuration by avoiding the limitations of skin movement artefact when compared to individual skin markers (Manal et al., 2000).

3.2.3.2 Electromyography (EMG) analysis.

EMG data capture procedure

EMG data were collected using a Direct Transmission System (DTS) with 16 channels (Model 586 Tele Myo DTS Desk Receiver, Noraxon inc., USA) (Figure 3-7a). The DTS sensors (model 542) were used and EMG lead (542AP) set was inserted into each EMG probe (Figure 3-7 b). The data were synchronised into Qualisys Track Manager for the data collection of the movement tasks. For the maximal voluntary contractions EMG data were sampled at 3000 Hz.

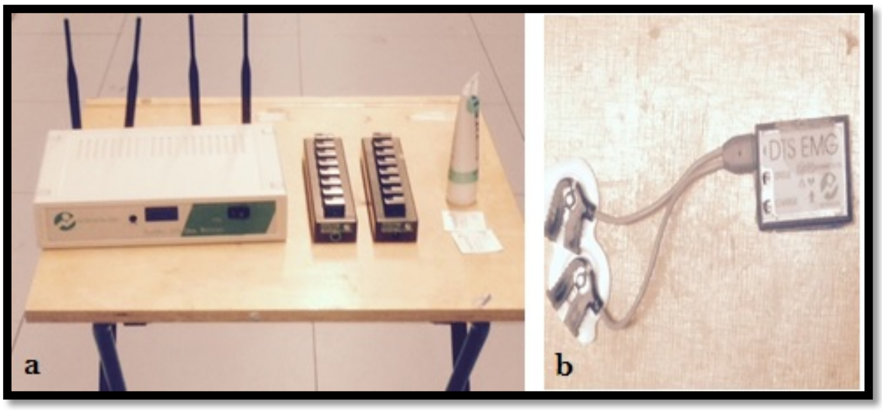


Figure 3- 7: The EMG capture system. a. direct transmission system with 16 channels, b. the DTS sensors.

The muscle activity of each participant was recorded from four muscles: Biceps Femoris (BF), Semitendinosus (ST), Vastus Lateralis (VL), and Vastus Medialis (VM). The electrodes placement over the skin of each of previously mentioned muscles was according to the widely used SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) guidelines (http:// www.seniam.org) (Hermes et al., 1999).

The surface EMG electrodes were placed parallel to muscles fibres on lower limbs : located over the muscle belly of vastus Medialis (at 80% on the line between ASIS and the joint space in front of the anterior border of the medial ligament) and vastus Lateralis (at 2/3 on the line from ASIS to the patella lateral side) while the participants were lying on their back and then over the muscle belly of Semitendinosus muscle (at 50% on the line between the ischial tuberosity and the medial tibia epicondyle) and Biceps Femoris muscle (at 50% on the line between the ischial tuberosity and the lateral tibia epicondyle) whilst the participants were lying on their front. The skin over each previously mentioned muscles location was prepared for electrode by shaving and light abrasive skin prepping (Nuprep Gel) was applied to the electrode site with a gauze pad; than rubbed lightly onto the skin and then rubbed off with clean gauze pad so that any dead skin was swabbed off. After that, the skin area was cleaned with 70% isopropyl alcohol and left for two minutes to dry. Self-adhesive Ag/AgCl bipolar dual surface electrodes (Figure 3-7b) was placed over the preparation sites in line with the muscle fibres. Once the surface EMG electrodes placement was completed, the electrodes and transmitters were secured with a crepe bandage (Fabriofoam, USA ,5cm x 2m) and athletic tape to minimise any movement artefact. To insure proper electrode placement was verified via manual muscle testing (Hislop et al., 1995).

EMG Maximum voluntary isometric contraction data collection

The order of the muscle testing during maximal voluntary isometric contraction (MVIC) assessment was randomised. All participants were asked to do a five-minute warm-up before the assessments; they had a thirty-second rest between each trial and a three-minute rest between each side to reduce the effect of fatigue (Norcross et al., 2010). Each muscle MVIC was performed three times. For the hamstrings MVIC, the participants were positioned on a lab bench with 20° of knee flexion and then asked to perform flexion contraction for approximately five seconds against the manual resistance of the investigator. For the quadriceps MVIC, participants were asked to sit with their hips and knees at 90° flexion, and then were asked to perform maximum knee extensions for approximately five seconds against the manual resistance of the investigator (Palmieri-Smith et al., 2009; Letafatkar et al., 2015).

3.2.3.3 Study Tasks.

ACL injuries usually occur when an athlete is performing a single legged manoeuvres (Monajati et al., 2016; Kristianslund and Krosshaug, 2013). Functional screening tasks for the risk of ACL injury tend to focus on landing tasks, which may be limited in sports where changing direction maneuvers are the main mechanism for sustaining NCACL injury. The majority of NCACL injuries are an outcome of changing direction horizontally such as pivoting and cutting (Faude et al., 2006). Several studies documented gender difference in 45° side-step cutting have been observed in knee angles in collegiate basketball athletes (Mclean et al., 2005) and football athletes (Beaulieu et al., 2008, Mclean et al., 2004).

Studies have demonstrated a relationship between single legged landing, pivoting and cutting functional tasks in terms of knee motion and moments (Jones et al., 2014; Alenezi et al., 2014; Whatman et al., 2011; Harty et al., 2011; Mclean et al., 2005). The SLS and SLL tasks were reported to be more appropriate for assessing athletes who are at higher risk of ACL injury (Jones et al., 2014: Gwynne and Curran, 2014; Herrington et al., 2017). Both tasks are unilateral functional tasks, which will help to identify the risk for each lower limb a lone as most knee and ACL injuries occurs during single legged movements (Alenezi et al., 2014; Herrington et al., 2017). This would make it more sensible and realistic to assess the level of suspected alteration in lower limb mechanics patterns while performing a high risk task which would challenge knee stability and could put the knee at risk of a NCACL injury during training or competition (Munro et al., 2012; Jones et al., 2014: Gwynne and Curran, 2014; Alenezi et al., 2014; Herrington et al., 2017). Therefore, three single legged manoeuvres were chosen as the three test conditions, which were Single Leg Squat (SLS), Single-Leg Landing (SLL) and Single-Leg Stance.

Single Leg Squat (SLS) task

This is a common task (Figure 3-8) used by researchers when assessing the musculoskeletal performance of the lower extremities (Weeks et al., 2012). The SLS task is a simple method of identifying abnormal patterns in order to assist clinicians during the diagnosis and screening of individuals (Alenezi et al., 2014; Dwyer et al., 2010; Ortiz et al., 2010; Zeller et al., 2003). During the performance of the SLS task, there is an increased challenge on the motor control of the different lower limb joints (Di Mattia et al., 2005; Zeller et al., 2003).

Each participant was instructed to stand on one leg during the trials while holding the other leg at approximately 45° of knee flexion without allowing the legs to contact each other. Each participant was instructed to squat down with an acceptable minimum of 45° of knee flexion (Nguyen et al., 2011; Nakagawa et al., 2012b), and return to a single leg stance while maintain their balance. The knee flexion angle was checked during practice trials using a standard goniometer (Gaiam-Pro) and then observed by the same examiner throughout the trials. In addition, in order to reduce the effect of the velocity of the movement, each trial was performed with a five-second count, by which the first second initiated the start of the trial, the third second required the participant to be at their maximum knee flexion point, and the fifth second indicated the end of the trial (Herrington et al., 2017; Alenezi et al., 2014). This all ensured standardisation of the approach for all participants.

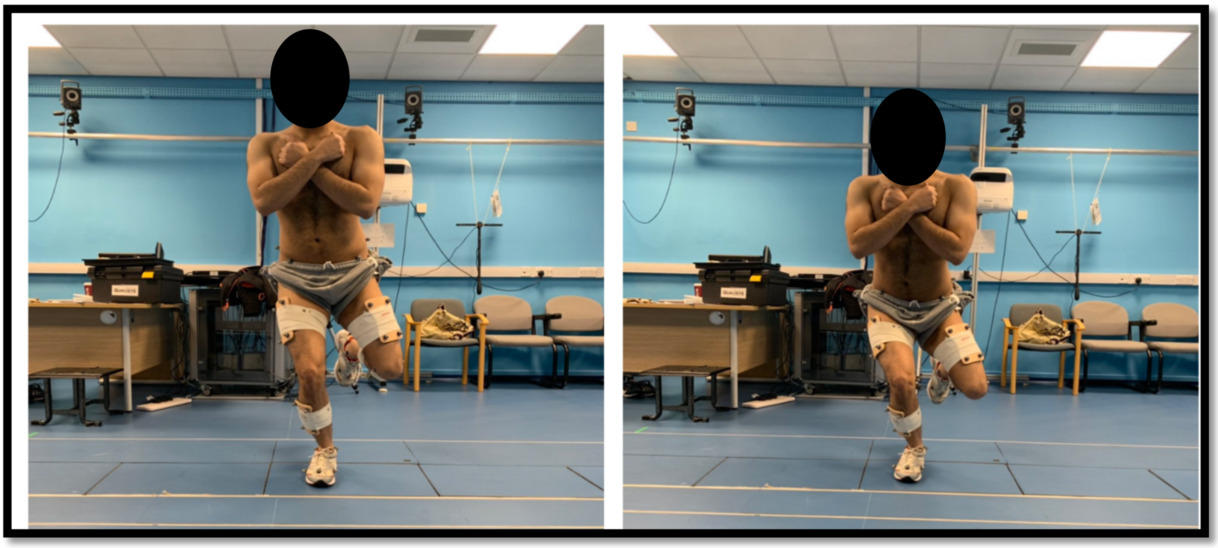


Figure 3- 8: SLS task

Single Leg Landing (SLL) task

The single leg landing (SLL) task (Figure 3-9 a-b) is another task which challenges the dynamic stability of the three main joints of the lower limb, especially the knee joint (Yeow et al., 2010). Single leg landing is considered a common manoeuvre in sport (Pollard et al., 2010; Faude et al., 2006; Mclean et al., 2005). During landing a misalignment of the lower limb may happen, which may potentially be related to poor neuromuscular control (Mclean et al., 2005).

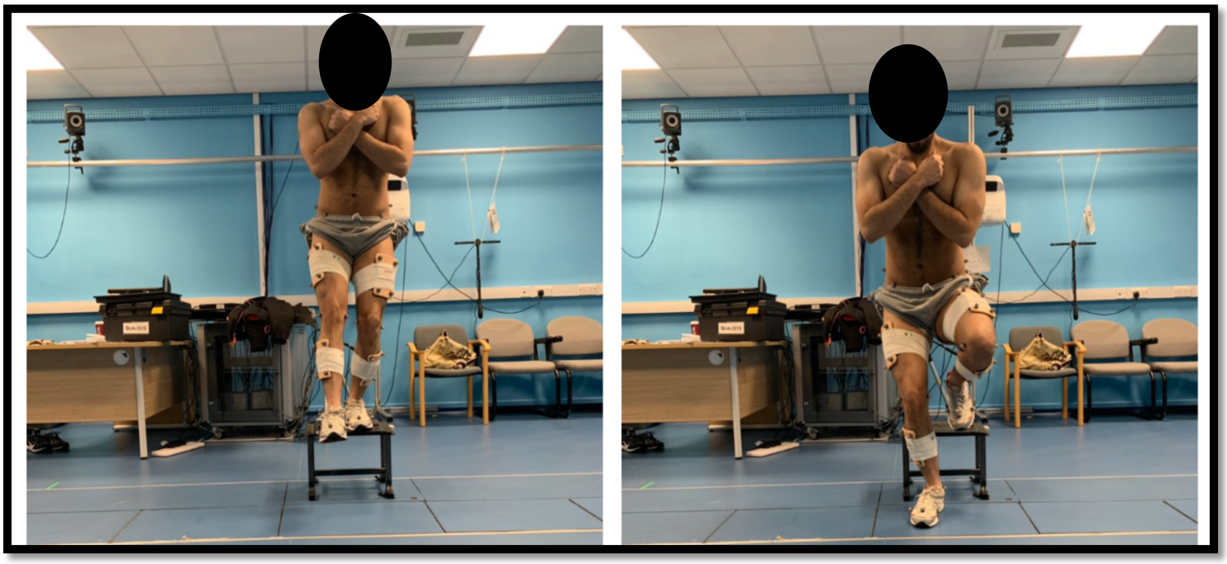


Figure 3- 9:SLL task. a. starting position, b. ending position.

Studies evaluated SLL while landing from 30 cm high platform (Nagano et al., 2007; Schmitz et al., 2007; Ford et al., 2010; Jones et al., 2014). Therefore, the same height step was used in current study (a height of 30 cm) which is based on typical jump height of female athletes (Zainal et al., 2013). Every trial was observed by the same examiner throughout the trials to ensure that a 30 cm drop height was achieved. Each participant was instructed to ensure a homogeneous landing distance in every trial, making sure that the participant landed the full 30 cm from the raised platform. Trials were disqualified if participants were deemed to step down during the task. Each participant was asked to lean forward and drop vertically onto a mark 30 cm from the platform on the middle point of the force platform which was marked, holding the position on landing for a second. Each participant was asked to complete five successful trials for each of the tasks.

Single-Leg Stance task

Sensorimotor system is responsible for regulation functional stability of the knee joint during voluntary movement (Lehmann et al., 2017). Thus, postural stability is considered as an important criterion to determine the functional movement that reflected a multimodal interaction of the sensorimotor system (Shumway-Cook et al., 2012). Until now there has been no gold standard to assess postural stability. However, the CoP trajectories are usually evaluated by lab based pressure sensitive or force platforms in order to measure postural stability (Lehmann et al., 2017; Qu et al., 2015; Huurnink et al., 2013; Clark et al., 2010). The utilisation of center of pressure (CoP) trajectories, as the vector of total force applied to the center of the supporting surface (Winter et al., 1990). Several studies have used the 10-second Single-Leg Stance task to assess the participant postural stability (Soltani et al., 2014; Dauty et al., 2010). Therefore, same stance period was used in current study. Each participant was asked to stand on she/he supportive leg on the reference point at the force plate while their eyes were open (Figure 3-10) and stand still for 10 seconds. During the single leg stance, the knee was slightly flexed which was more natural

Figure 3- 10: Single Leg Stance task

3.2.3.4 Conducting the tests.

Upon arrival to the human performance lab, participants were briefed regarding the study and the objectives of the investigations, and the study equipment was explained to them as well. They were then asked to complete and sign the informed consent form and health history questionnaire which included demographic information on the participants. Prior to the first session, participants wear a comfortable t-shirt and a pair of shorts, then they performed five min of low intensity warm-up stretching. Afterwards, participants were prepared for EMG measurement and completing the collection of MVIC data, participants followed the same collection procedure described previously in section 3.2.3.2 on EMG data collection.

The participants wore standard lab shoes (New Balance, UK) to keep the consistent interface between shoe sole and the floor surface. Before commencing the test, the main researcher placed a total of 40 markers to the participants' lower limbs, as explained above in section 3.2.3.1. After completing 3D marker attachment, participants were instructed to stand in a stationary position, with arms crossed over the chest, to avoid obstruction of any markers during the static trials capture. Following the completion of the static standing trials, the anatomical markers were removed, and participants were instructed to start to perform the designed tasks in a randomized sequence. In order to limit systematic bias, participants were given an opportunity to familiarize with the study tasks, prior to engaging in tasks. They were requested to practice each task until they felt comfortable with them, which usually took three to four trials until they were confident they could perform the task correctly.

The sequence of the tasks (either Single-Leg Squat (SLS) or Single-Leg Landing (SLL) or Single-Leg Stance tasks) were randomly determined by asking the subject to choose one card from the three cards (each card for one condition). The randomisation of tasks by using cards were the same followed throughout the follow-up assessment. Every participant was instructed to perform each task SLS, SLL and Single-Leg Stance tasks five trials for each task. To limit systematic bias each participant was requested to practice SLS, SLL and Single leg stance tasks until he/she felt comfortable with performing the task; which usually took three to four trials until he/she was confident to perform the task correctly. In addition, to avoid any potential fatigue effect, participants were allowed thirty-second rest between each trial and a three-minute rest between each task (Munro et al., 2012; Cortes et al., 2011; Norcross et al., 2010). The non-dominant leg (supportive leg) was the side assessed. The dominant (preferred) leg was defined as the leg used to kick a ball a maximum distance (Ford et al., 2003; Hewett et al.,2005; Zazulak et al., 2005; Palmieri-Smith et al., 2008,2009; Norcross et al., 2010; Harty et al., 2011; Mizner et al., 2012; Nilstad et al., 2014; Dawson et al., 2015; Letafatkar et al., 2015).

After concluding the first session, all 3D markers and EMG electrodes were removed from participants, and they had a minimum one-hour break. After one hour, participants returned to the lab, and the above outlined procedure was repeated in order to collect study data for the second reliability session. After a period of one week, participants again returned to the lab to perform the third and final reliability session. The same motion analysis and EMG system setup used in the first reliability session and described in the sections on method and procedures, data collection, and tasks was prepared. Each of the three reliability sessions lasted for approximately 120 -90 min.

3.2.4 Data Processing.

3.2.4.1 3D data.

The static trial allows the position of the anatomical markers as reference points to identify bone movement through the tracking markers (technical markers) during the dynamic trials.

Following the collection of the static and the dynamic trial data of each participant, all data were processed in Qualisys Track Manager (QTM) software (Version 2.15), then each marker was labelled (Figure 3-11a) and any abnormal movements in the marker trajectories were corrected. Gaps in kinematic data were interpolated to ensure gaps of no more than 10 frames to be filled. All the static and dynamic trials were then exported as a C3D file for further analysis in Visual 3D motion software (Version 6.0, C. Motion Inc., USA).

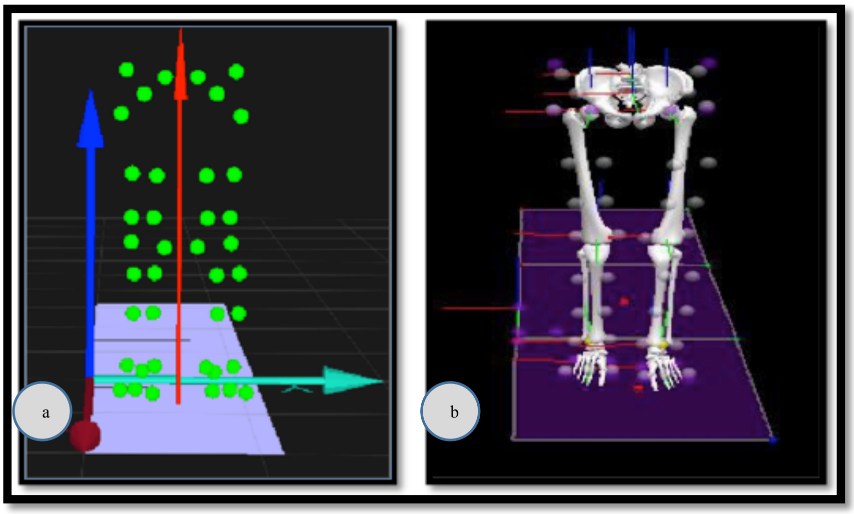


Figure 3- 11: (a) Labelled markers in QTM. (b) V3D bone model (anterior view).

The calibration anatomical system technique (CAST) was used to determine the six-degree of freedom movement of each segment and anatomical significance during the dynamic trials. The static trial position was designated as the participants natural (anatomical zero) alignment, subsequent kinematic measures were related back to this position which contained of seven rigid segments (Figure 3-11b). Each segment and joint in the built model would consist of six variables that described its position in three-dimension space, were three variables describe the segment translation in three perpendicular axes (Vertical, anterior-posterior, and medial –lateral), three variables describe the rotation about each axis of the segment (frontal, sagittal, and transverse). Additionally, the hip joint centre was automatically calculated using ASIS and PSIS markers using the regression equation from by Bell and Brand (1989). Visual3D motion (Version 4.23, C-Motion Inc. USA) was used to calculate the joint kinematic and kinetic data. Motion and force plate data were filtered employing a Butterworth 4th order bi-directional low-pass filter with cut-off frequencies of 12 Hz and 25 Hz, respectively, with the cut-off frequencies based on a residual analysis (Yu et al., 1999). The main purpose of smoothing data by using digital filters is to reduce or minimise any random noise while preserving the signal un-affected (Payton et al., 2008).

All lower limb segments were modelled as conical frustra, with inertial parameters estimated from anthropometric data (Dempster et al., 1959). Joint kinematic data was calculated using an X-Y-Z Euler rotation sequence. Joint kinetic data were calculated using 3D inverse dynamics, and the joint moment data were normalised to body mass and presented as external moments referenced to the proximal segment. External moments were described in the current study for example, an external knee flexion load will tend to flex the knee joint and an external knee valgus loads will lead to abduction the knee joint (valgus position) (Malfait et al., 2014). The following discrete variables were calculated for trial: peak of hip adduction, internal rotation, knee valgus, flexion moments, and peak of lower limb joint angles at sagittal, frontal and transvers planes for the hip, knee and ankle.

During the single leg landing (SLL) task (Figure 3-12) the dynamic events were defined from 15 degrees of knee flexion, after initial contact of the leg, and ended at maximum knee flexion of the same leg. For the single leg squat (SLS) tasks, the starting event was when the knee passed 15 degrees of knee flexion during the descent phase, and ended at maximum knee flexion (Figure 3-12). The kinematic and kinetic variables were normalised to 100% of these phases during the tasks. Initial ground contact (IC) was defined as the instance when the ground reaction force (GRF) exceeded 20 newton (N) (Alenezi et al., 2014). For the postural stability examination, of the centre of pressure excursion, during the Single Leg Stance the events were determined from IC for a period of 10 seconds with the knee flexed approximately 15 º (Figure 3-12).

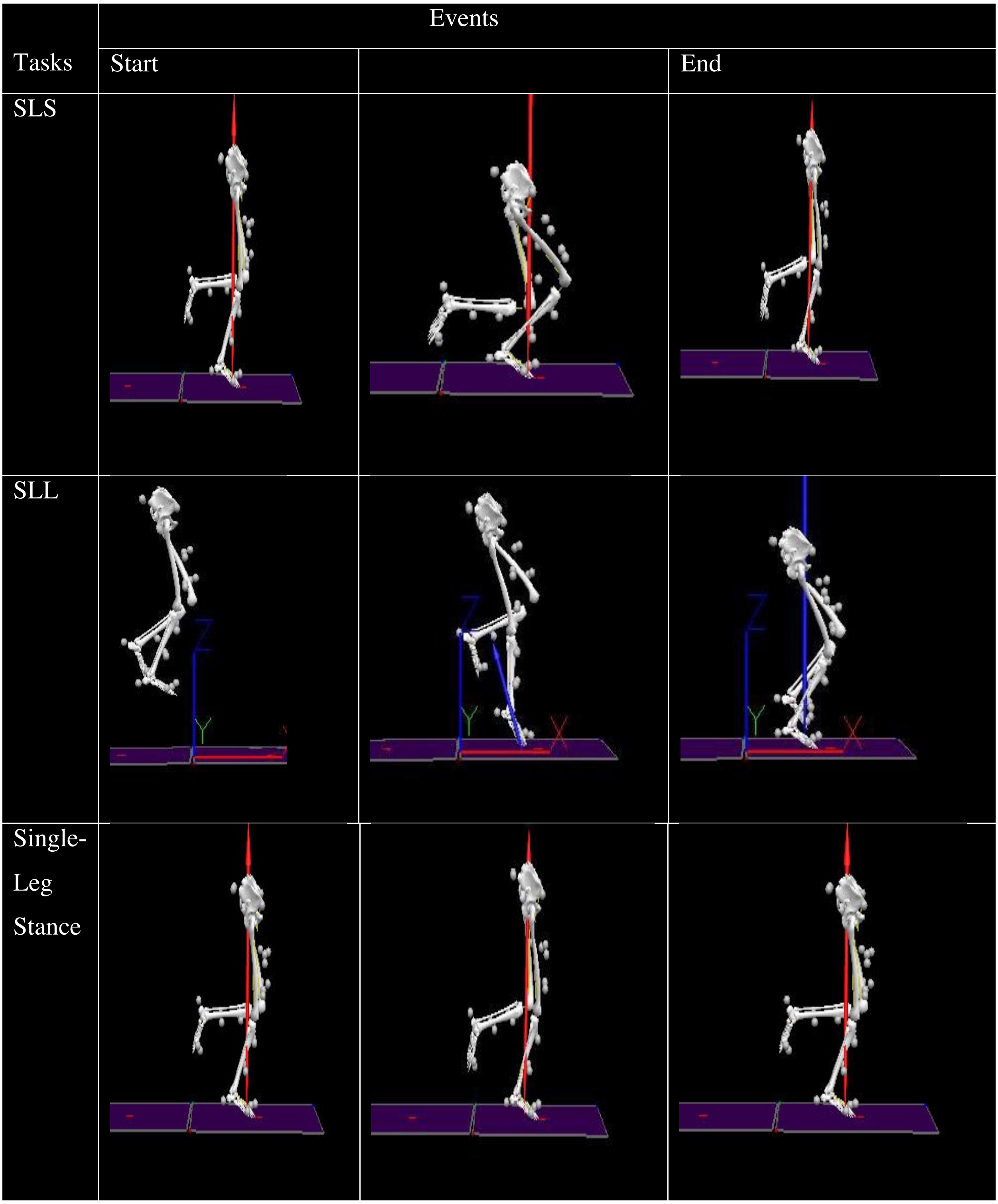


Figure 3- 12: Illustration the event sequence during the SLS and SLL tasks.

3.2.4.2 EMG data.

All EMG data of SLL, SLS, and MVIC trials were filtered with the bandwidth pass filter of (20-450Hz) (Zebis et al., 2008; Palmieri-Smith, et al., 2009), using a Butterworth filter (4th order, zero-phase leg). The data were rectified and smoothed by taking the root mean square average of the EMG signal using a 100 millisecond sliding window function (De Ste Croix et al., 2015). The average of the EMG peak value from the three recorded trials, which represented the MVIC, was used for the normalisation of the dynamic peak EMG data collected on each muscle tested during SLS and SLL tasks. Thus, EMG data were expressed as a percentage of MVIC (% MVIC).

The average peak EMG value of each muscle during the three MVIC trials was used to normalise the dynamic EMG data collected during SLS and SLL tasks for each muscle tested. Thus, EMG data were expressed as a percentage of MVIC (%MVIC). The EMG data was collected from four muscles: Vastus medialis (VM), Vastus lateralis (VL), Semitendinosus (ST), and Biceps femoris (BF). The following data were obtained from EMG with the peak amplitude during the dynamic trials. This was used to calculate the co-contraction index between the agonist and antagonist muscles. The Quadriceps and Hamstrings co-contraction were assessed during single leg squat (SLS) and also during the feed forward (pre-landing phase 100 ms prior initial contact to ground) and feedback phase (landing phase 100 ms after initial contact to ground) of single leg landing task (SLL).

The (VL-BF) co-contraction index for the lateral knee muscular and (VM-ST) co-contraction index for the medial knee muscular were calculated using the following equation ⦃**(EMGS/EMGL) x (EMGS+EMGL)**⦄ (Rudolph et al., 2001). This method provided an estimation of the relative activation of the pair of the muscle as well as the magnitude of the co-contraction (Rudolph et al., 2001). Where EMGS is the level of activity in the less active muscle and EMGL is the level of activity in the more active muscle. This method will provide an estimate of the relative activation of each pair of muscle as well as the magnitude of the muscle co-contraction index (Rudolph et al., 2001). The ratio of medial to lateral co-contraction will determine whether co-contraction between both sides of the thigh is imbalanced. The ratio of the medial knee muscular (VM-ST) to lateral knee muscular (VL-BF) co-contraction index will be calculated by dividing the medial (VM-ST) co-contraction index by the lateral (VL-BF) co-contraction index (Palmieri-Smith et al., 2009; Letafatkar et al., 2015; Mohr et al., 2017).

3.2.4.3 CoP-Excursion.

Various parameters have been employed to assess postural stability (Landry et al., 2010; Farzadi et al., 2017). The single leg stance allows for the assessment of balance under conditions that introduce additional challenges to the postural-control system to make more adjustments in order to prevent a fall (Steffen et al., 2017; Palmieri et al., 2002). The most common and reproducible methods for quantifying standing balance is based on Cop trajectories measures (CoP-Excursion) (Steffen et al., 2017; Lin et al., 2008; Gerbino et al., 2007; Karst et al., 2005).

The single leg standing test consisted of five trials for 10 second period (Nigg et al., 2006) each while standing on single leg (supportive limb) on the force plate to determine the anterior-posterior and medial-lateral excursion of the centre of pressure (CoP). The force platform data exported into V3D. This was quantified balance based on CoP measures on force palate, the measures of range of motion of CoP in medial-lateral (ML) and anterior–posterior (AP) direction. The total CoP excursion was calculated using Excel sheet X (anterior–posterior)-Y (medial–lateral) average range.

3.2.5 Outcome measures.

3.2.5.1 Primary outcome measures.

The primary outcome measures for the study were as follows:

Biomechanical parameters

The magnitudes of the knee valgus angle and moments recorded at the peaks values from five trials during the tasks were considered as the primary outcome measures. Theyhave been the most common variables assessed in the literature (The mean of peaks of the knee valgus angle and moments) during the period from the initial contact to the task ends (Palmieri-Smith et al., 2008, 2009; Letafatkter, et al., 2015). Peak knee valgus loads have been considered one of the most recognizable risk factors for NCACL in female athletes during athletic activities (Hewett et al., 2005).

Electromyography parameters

The muscle recruitment patterns for the quadriceps and hamstrings of limbs were evaluated to determine the medial knee muscular (VM-ST) co-contraction index and the lateral knee muscle (VL-BF) co-contraction index and the ratio of the medial knee muscle (VM-ST) to lateral knee muscular (VL-BF) co-contraction index. The muscle co-contraction was determined using the equation described by Rudolph et al. (2001), which has been employed in previous studies (Palmieri-Smith et al., 2009; Murley et al., 2010; Letafatkar et al., 2015; Mohr et al., 2017).

$$\{(\mathrm{EMGS}/\mathrm{EMGL}) \times (\mathrm{EMGS} + \mathrm{EMGL})\}$$

CoP-Excursion parameters

Various parameters employed to assess postural stability (Palmieri et al., 2002). The range of motion difference between the maximum magnitude which is the maximum absolute displacement of the CoP from its mean, whereas, minimum magnitude is the minimum displacement of the CoP from its average point (Landry et al., 2010; Palmieri et al., 2002). The single leg stance allows for the assessment of balance under conditions that introduce additional challenges to the postural-control system to make more adjustments in order to prevent a fall. Single leg stability was the quantified balance ability based on CoP-Excursion measures on force plate, the measures of range of motion of CoP-Excursion in medial-lateral (M/L) and anterior posterior (A/P) direction. The parameters are one dimensional, allowing for assessment of postural control in both A/P and M/L directions. The total CoP- excursion was determined by calculating Excel sheet A/P(x)-M/L(y) average range. The following formulas used to calculate variables for CoP excursion data:

$$\sum_{i=0}^{100}\binom{n}{i}=\surd(X_{i+1}-X_i)^{2}+(Y_{i+1}-Y_i)^{2}$$

3.2.5.2 Secondary outcome measures.

The other kinematic and kinetic measures, of the peak values of the joint angles and moments of the adjacent joints and planes were also assessed which included the Hip adduction angle and moment, Hip flexion angle, Hip internal rotation, Dorsiflexion angle and moment and

(GRF) Ground reaction force GRF).

3.2.6 Data Analysis.

Statistical analysis was performed with SPSS (version 23.0. IBM SPSS Statistics, USA). The mean of the individual trial peak values from five trials, from the first and third sessions, was used for between-day reliability, and the mean of the first and second sessions was used for the within-day reliability. Intra-class correlation (ICC) was used to assess relative reliability model 3.k, were the first number point out the use of the two-way mixed model of ICC, whereas the second number would represent the use of an average measurement (Portney and Watkins,2009: Koo et al., 2016). Levels of ICC were interpreted according to criteria (Coppieters et al., 2002) illustrated in Table 3-3. Similar data analysis criteria previously mentioned in chapter three (section 3.1.5) were used. Both SEM & MDD are expressed in the units of the measurement tool used (degrees for joints angles and Nm/kg for joint moments) (Blankevoort, et al., 2013).

3.2.7 Results.

3.2.7.1 Participants.

The demographic characteristics of eleven recreationally active participants, which is summarised in Table 3-4.

Table 3 - 1: Study sample characteristic.

Gender	Females (N=6) Mean ±SD	Males (N=5) Mean ±SD
Age (years)	23±4.2	26.2±5.4
Height (cm)	165±7.5	179±6.1
Mass (kg)	62.5±8.2	76.2±5.6

3.2.7.2 Test-retest reliability of 3D data.

Table 3 -5: Within- and Between-day ICC, Mean, SEM, and MDD values for 3D variables during SLS Tasks.

Variable	Within-day SLS				Between-day SLS			
	ICC(95%CI)	Mean	SEM	MDD	ICC(95%CI)	Mean	SEM	MDD
Joint angle (Degrees)								
Hip Adduction	0.95(0.86-0.99)	10.26	1.08	2.92	0.84(0.59-0.94)	10.08	2.28	6.21
Hip Flexion	0.93(0.81-0.98)	77.68	2.74	7.39	0.90(0.72-0.97)	78.28	2.77	7.47
HipInt Rotation	0.93(0.81-98)	6.98	1.12	3.02	0.79(0.48-0.93)	5.75	2.52	6.80
Knee valgus	0.87(0.66-95)	-3.91	0.91	2.24	0.90(0.72-0.97)	-4.38	0.94	2.53
Knee Flexion	0.93(0.81-0.98)	82.24	2.12	5.72	0.91(0.75-0.97)	82.09	1.75	4.73
Dorsiflexion	0.92(0.78-0.97)	35.87	0.93	2.51	0.86(0.64-0.95)	36.85	1.36	3.67
Moments (Nm/kg)								
Hip adduction	0.88(0.68-0.96)	0.97	0.08	0.22	0.78(0.46-0.92)	0.90	0.07	0.19
Knee valgus	0.90(0.72-0.97)	0.10	0.02	0.05	0.78(0.46-0.92)	0.11	0.02	0.05
Knee flexion	0.92(0.78-0.97)	1.82	0.05	0.14	0.90(0.72-0.97)	1.78	0.06	0.16
Dorsiflexion	0.86(0.64-0.96)	1.10	0.06	0.16	0.88(0.68-.096)	1.11	0.04	0.11
Force Bodyweight	0.95(0.86-0.98)	1.12	0.03	0.08	0.87(0.66-0.95)	1.14	0.02	0.05

Table 3 -6: Within- and Between-day ICC, Mean, SEM, and CV% values for 3D variables during SLL tasks.

Variable	Within-day SLL				Between-day SLL			
	ICC(95%CI)	Mean	SEM	MDD	ICC(95%CI)	Mean	SEM	MDD
Joint angle (Degrees)								
Hip Adduction	0.92(0.78-0.97)	6.13	1.14	3.07	0.86(0.64-0.96)	5.24	2.27	6.12
Hip Flexion	0.90(0.72-0.97)	70.77	3.12	8.42	0.75(0.40-0.93)	67.84	3.96	10.69
Hip Int Rot	0.93(0.81-98)	6.31	1.35	3.65	0.79(0.48-0.93)	5.35	2.37	6.39
Knee valgus	0.86(0.64-0.96)	-5.39	1.07	2.88	0.90(0.72-0.97)	-6.93	0.84	2.30
Knee flexion	0.86(0.64-0.96)	74.58	1.74	4.69	0.93(0.81-0.98)	74.21	1.16	3.13
Dorsiflexion	0.91(0.75-0.97)	30.79	1.37	3.69	0.91(0.75-0.97)	30.78	1.39	3.75
Moments (Nm/kg)								
Hip adduction	0.79(0.48-0.93)	1.18	0.09	0.24	0.78(0.46-0.92)	1.20	0.10	0.27
Knee valgus	0.75(0.40-0.93)	0.23	0.02	0.05	0.75(0.40-0.93)	0.23	0.05	0.14
Knee flexion	0.92(0.78-0.97)	2.15	0.09	0.24	0.75(0.40-0.93)	2.21	0.15	0.41
Dorsiflexion	0.88(0.68-0.96)	1.67	0.09	0.24	0.86(0.64-0.96)	1.75	0.12	0.32
Force(Body weight)	0.94(0.83-0.98)	2.37	0.07	0.19	0.85(0.62-0.95)	2.38	0.17	0.46

In the SLS task within-day ICC values achieved a range of 0.87-0.95 for angles and 0.86-0.92 for moments which were higher than between-day ICC values which ranged between 0.79-0.91 for angles and between 0.78-0.90 for moments. In general, all SLS ICC values were good to excellent, where the lowest ICC values during SLS task was for the hip adduction and knee valgus moments 0.78. The SEM values range between 2.96º -0.91° for the joints angles and 0.08 -0.04Nm/kg for moments were the SEM values for the hip internal rotation angle was the highest 2.96°.

In the SLL task within-day ICC values achieved a range of 0.86-0.93 for angles and 0.75-

0.92 for moments which were higher than between-day ICC values with a range of 0.75-0.93 for angles and 0.75-0.86 for moments. In general, all SLL ICC values indicated from good to excellent reliability. The SEM values range between 3.87-0.69° for the joints angles and 0.12-0.07 Nm/kg for moments were the SEM values for the hip flexion angle was the highest 3.87°.

The within-day ICC values for all variables 0.86-0.95 for joints angles and 0.70-0.92 for joint moments were generally greater than between-day ICC values 0.75-0.93 for joint angles and 0.75-0.90 for joint moments. The within- and between-day SEM values for joint moments were lower than kinematic SEM values. Kinematic values for within- and between-day sessions ranged between 3.87-0.69° while SEM for joint moments ranged between 0.12-0.04 Nm/kg. The highest SEM value across all tasks was found in hip flexion SEM = 3.87°, which took place during the between-day SLL task.

3.2.7.3 Test-retest reliability of EMG data.

During the SLL task the EMG data Vastus Medialis and Semitendinosus (VM-ST) co-contraction index and the Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index during feedforward motor control phase (pre-landing phase) of the SLL task shown at Table 3-7, which had a dynamic window of 100 ms prior to initial contact with the ground, the EMG outcomes analysis demonstrated a good range of reliability with between day ICC values range between 0.75-0.81 which slightly higher than their between-day ICC values. Moreover, during the feedback motor control phase (post-landing phase) of the SLL task shown at Table 3-8, which, had a dynamic window of 100 ms after initial contact with the ground, the EMG analysis demonstrated, the ICC values ranged between 0.70-0.77 showing good level of reliability (Coppieters et al., 2002).

The medial to lateral muscle co-contraction ration during feedforward and feedback motor control phase SEM values ranged between 0.101 to 0.165 %MVIC. Furthermore, Medial knee muscular co-contraction to lateral knee muscular co-contraction ration during the feedforward motor control phase showed a higher between-day ICC values 0.80 in compere with the ICCs between-days values for feedback motor control values 0.77. The ICC values for medial to latera co-contraction ration ranging from 0.70 to 0.80, which would be considered good level of reliability (Coppieters et al., 2002). In addition, the SEM values ranged between 3.59 and 5.52 %MVIC for media (VM-ST) and lateral (VL-BF) co-contraction for feedforward and feedback motor control phases, respectively, during SLL tasks.

During the SLS task the medial side (VM-ST) and lateral side (VL-BF) knee muscles co-contraction during the SLS task Table 3-9, showed ICC values 0.80 and 0.87, respectively which would be considered a good level of reliability (Coppieters et al., 2002). Additionally, the media (VM-ST) to lateral (VL-BF) co-contraction ration during SLS task demonstrated an excellent level of reliability, with between day ICC values of 0.97 (Coppieters et al., 2002). In regarding the SEM values ranged between 4.02 and 4.67 %MVIC for media (VM-ST) and lateral (VL-BF) co-contraction during SLS tasks, whereas the medial to lateral muscle co-contraction during SLS showed SEM value of 0.107 %MVIC.

3.2.7.4 Test-retest reliability of CoP-Excursion.

The mean, 95% confidence intervals (CI), standard error of measurement (SEM), and minimum detectable difference (MDD) of CoP-Excursion Variables Single Leg Stance tasks is illustrated, in Table 3-9. The CoP Excursion values showed good level of reliability, with the between-days ICC values 0.88, which ranged between 0.68 – 0.96. The SEM values were 4.01 millimetre and the MDD values were 11.12 mm.

Table 3 - 2: Between-day ICC, Mean, SEM, and MDD values for s EMG variables during the SLL task at Feedforward (pre-landing) motor control phase (% MVIC).

Variables	ICC (95% CI)	Mean %MVIC	SEM %MVIC	MDD %MVIC
VM-ST CCI	0.75(0.40-0.93)	33.85	3.59	9.95
VL-BF CCI	0.81(0.52-0.93)	43.55	4.84	13.41
Med /Lat ratio	0.80(0.50-0.92)	0.78	0.101	0.28

Table 3 - 3: Between-day ICC, Mean, SEM, and MDD values for surface EMG variables during the SLL task at Feedback (post-landing) motor control phase (%MVIC).

Variables	ICC (95% CI)	Mean	SEM	MDD
VM-ST CCI(%MVIC)	0.70 (0.31-0.89)	34.35	5.52	15.3

VL-BF CCI(%MVIC)	0.70 (0.31-0.89)	39.25	4.30	11.91
Med / Lat ratio	0.77 (0.44-0.91)	0.95	0.165	0.46

Table 3 - 4: Between-day ICC, Mean, SEM, and MDD values for surface EMG (MVIC%) variables during the SLS task and CoP-Excursion (mm) variables during the Single Leg Stance task.

Variables	ICC (95% CI)	Mean	SEM	MDD
VM-STCCI (%MVIC)	0.80(0.50-0.92)	36.55	4.67	12.95
VL-BF CCI (%MVIC)	0.87(0.66-0.95)	43.70	4.02	11.14
Med/Lat ratio	0.95(0.86-0.98)	1.04	0.107	0.29
CoP-Excursion(mm)	0.89(0.70-0.96)	32.78	4.01	11.12

3.2.8 Discussion.

The objective of this chapter were to evaluate the reliability of using a 3D motion analysis system to assess the within and between-day reliability of kinematic and kinetic biomechanical variables, as well as, the between-day reliability of EMG variables, during SLS and SLL tasks in recreational athletes. In addition, to CoP-Excursion variable during single leg stance.

3D data

Similar to other research work the majority of between-day ICCs values for joint motion, moments and vertical GRF were less than within-day values across the study tasks. In a study by Ford et al. (2007) similar findings were reported during landing while performing drop vertical jump task, with within-day measurements showing excellent reliability for joint angles (ICC = 0.95) and good reliability for joint moments (ICC =0.84), while between-day reliability showed fair and good degrees of reliability (ICC=0.74 and 0.80, respectively). Furthermore, in a study by Alenezi et al. (2014) which was conducted in the same laboratory facilities and used same instrument used in the current study. The author reports its results for the SLL tasks showed excellent reliability (ICC=0.92) for joint angles, and good reliability for joint moments (ICC=0.82), during the within-day reliability session. While during the between –day session the level of reliability for joint angle and moments showed drop (ICC=0.80 and 0.75, respectively).

With respect to the vertical GRF data showed high level of reliability during all tasks, with ICC values for GRF range between (ICC= 0.94 to 0.85). This was in agreement with previous studies (Alenezi et al., 2014; Ferber et al., 2002; Kadab et al., 1989). Nonetheless, high reliability of GRF may be explained by GRF measures results of the sum of all body segmental acceleration, masses and gravitational forces. Thereby, no need for markers to collect GRF data, thus GRF data was not influenced from marker-positioning error and can be considered to be more repeatable (Ferber et al., 2002; Winter et al., 1995).

Several factors have been documented to influence both within- and between-day reliability measures, such as task difficulty, referenced static alignment, and skin marker movement (Ford et al., 2007; Ferber et al., 2002; Manal et al., 2000). Marker reapplication has been pointed out as a factor influencing the variability of between-day measures (Kadaba et al., 1989). In the current study, only the principle researcher did the placement of skin markers in all sessions. The reduced between-day ICC values indicate that the differences in marker replacement between the sessions influenced the reliability. Thereby, the employment of CAST marker-based protocol to limit the variability within this study from potential marker replacement error (Cappozzo et al., 1995). Therefore, it was adapted in this study. The use of the CAST marker-based protocol would offer improved anatomical relevance compared to the other marker set methods, which is known to offer an improved anatomical relevance, when compared to the modified Helen Hayes marker set (Kadaba et al., 1989). Furthermore, the CAST marker-based protocol attempted to decrease skin movement artefact by applying markers in the centre of the segments rather than close to the joints, as in the Helen Hayes model (Collins et al., 2009). In addition, a number of other measures were adapted to maximise the study reliability outcomes; from allowing sufficient rest periods between tests and trials to controlling the effects of fatigue and instructing participants to practice adequately before performing tests (Alenezi et al., 2014; Herrington et al., 2014; Munro et al., 2012; Norcross et al., 2010).

The current study provides SEM and MDD reference for SLS and SLL tasks, which may be useful for evaluating intervention outcome measurements Table 3-5 and 3-6 in particular for researchers and clinicians wanting to evaluate individual changes, the use of SEM and MDD is useful (Munro et al., 2012). The SEM measurement depends on the standard deviation measurements, which allows researchers to be 68% confident that the true value would be within ± 1 SEM of an observed value (Porteny and Watkins, 2009). Moreover, MDD is based on SEM, however, it is more conservative. Studies have reported that if the outcome measurements were larger than MDD values, it indicates that difference observed were not caused by subject's variability or measurement error with probability of 95% (Wilken et al., 2012; Ries et al., 2009).

Across all tasks for the kinematic and kinetic outcome measurements, the greatest SEM and MDD measures were found with hip-flexion angles during SLL task, particularly in between-day session (SEM=3.96°, MDD =10.69°). This could be explained by the larger range of movement in the sagittal plane when compared to frontal planes. In study by Nakagawa et al. (2014) reported lower SEM and MDD values for hip flexion angles during an SLS task during within-and between-days (SEM=2.6°,MDD=7.1°). This might be because the between-day interval was shorter than the current study (3 vs 7 days') and participants were younger than the current study participants (21±1.1 vs 24 ±5.8 years'), which may result in improved ICC values and subsequently lower SEM values.

EMG data

Surface EMG is considered a useful non-invasive method to study human movement which could investigate the activation amplitude and timing of muscular activation during various movement tasks such as walking, running and rehabilitation exercise (Benoit et al., 2003; Arokoski et al., 2004; Santilli et al., 2005; Sakamoto et al., 2009). During the different phase of the functional tasks, the knee muscles perform different functional roles as they shorten and lengthen during various loads (Chmielewski et al., 2005). This may induce muscular co-contraction strategies that are unique to each of tasks phases (Chmielewski et al., 2005; Hurd and Snyder Mackler, 2007).

The relative between-session reliability of muscular co-contraction index for the medial and lateral muscle of the knee joint for current study (ICC=0.70-0.87) demonstrated a good level of reliability (Coppieters, et al., 2002). Furthermore, it was similar to the results reported by Mohr et al. (2017) which showed ICC results (ICC=0.74-0.90). The positioning of electrode have been considered as source of error (Norcross et al., 2010). To reduce the error potential in the current study, standardized recommended procedures for surface EMG measurements (Hermens et al., 1999) were followed. Thereby, the influence of the study researcher on the EMG measurement errors in the current study is likely low. The majority of measurement errors in the co-contraction index of the medial and lateral knee muscles can be assign to intra-subject variability in the muscle recruitment patterns during study tasks, rather than the researcher influence (Mohr et al., 2017). The between-session measurement error in the ICC can be partially explained by intra-participant's variability while performing the functional tasks (Mohr et al., 2017).

CoP-Excursion

The centre of pressure excursion (CoP-Excursion), this parameter measures the average absolute displacement around the mean CoP and has been employed by different researchers (Farzadi et al. 2017; Plom et al., 2014; Price et al., 2013). The movement of the CoP trajectories varies depending on the movement of COM, and it also depends on the projection of the muscle forces required to control or produce movements (Palmieri et al., 2002). The CoP represents the weighted average of all pressures created from the area in contact with the support surface (Winter et al., 1990). Postural stability measures (CoP-Excursion) in this study has demonstrated good level of reliability (ICC =0.89) during single leg standing. This was similar to the results reported by Kouvelioti et al. (2015), the ICC values during single leg balance test were also considered good (ICC =0.87).

The generalisation of the current study outcomes is subjected to several limitations. For instance, these outcomes apply only to our laboratory setting and models. However, they are consistent with those previously reported. It has to be acknowledged that the current reliability study outcomes are limited to healthy population, which does not include ACL injured population. An additional limitation, was that the participants in this study all wore standard footwear (Lab shoes) on a mondo running surface, this would not recreate a typical footwear-surface interaction as in real game and practice.

3.2.9 Conclusion.

In general, the present study demonstrated good to excellent levels of relative reliability in within- and between-day sessions with low standard error of measurement. It has been shown in this section that the collection of 3D, surface EMG data during the single leg landing and single leg squat tasks. In addition, to postural stability measures during single leg stance tasks is a reliable tool to provide a quanitive measurement of lower limb kineamatic, kinatics and muscle recruitment pattern. Therefore, the intervention studies throughout this thesis could employ this measurement method to investigate the lower limb biomechanics and musclcular activity pattern in similer population of partcipants.

Chapter Four: The role of incorporating AposTherapy System on lower limb biomechanics in recreational female athletes with potential high risk for non-contact ACL injury – A feasibility study.

4.1 Introduction.

In this chapter, a feasibility study investigating the role of the AposTherapy intervention used in this thesis will be presented, as there are no previous studies in this area in this population. The first factor to consider was to determine the feasibility of running such a study and secondly whether any effect of the intervention program could be observed.

A feasibility study is described as a miniature version of the main study conducted prior to the main study to answer the question, 'can this study be done?' (Shanyinde et al., 2011; Arain et al., 2010). As such, feasibility studies play a preliminary role in the design stage of a larger trial to assess the methodological issues, safety, and efficacy (Eldridge et al., 2016; Shanyinde et al., 2011). It was also the need of the feasibility study to see if the various components of the study would work together. The components of the program involved an exercise program while wearing the AposTherapy system. The exercise elements were introduced with the aim to incorporate the AposTherapy system as balance exercise component in NMT program. Therefore, an exercise program was designed for the purpose of this study with the objective to gradually increase the challenge on neuromuscular stability while targeting a reduction in knee valgus alignment.

Therefore, it was hypothesised that incorporating the AposTherapy system as balance training component in NMT program aimed for female's recreational athletes with high risk of sustaining NCACL with impaired neuromuscular control will improve their lower limb neuromuscular control. Thereby, this may reduce the valgus loads on the knee joint.

4.2 Objectives.

The objectives for this feasibility study were twofold. Firstly, to evaluate the feasibility of performing the intervention on healthy recreational female athletes with the AposTherapy system and secondly to observe any alterations in the biomechanical risk factors associated with NCACL injuries. This was needed to be determined in the tasks chosen for the study as this had not been presented previously.

4.3 Method.

This was a feasibility study with repeated measures at two time points. All measurements were conducted at baseline and then after the 6-week intervention period, during which the intervention was removed when the participants were assessed. The University Research Ethics Committee approved this project (HSCR 13/69).

4.3.1 Participant.

As this was a feasibility study a small sample of five recreational active female staff and students was recruited from the University of Salford. The same inclusion and exclusion criteria which were previously stated at Chapter Three in section 3.2.2.1. Participants sports activities included Netball (2), Volleyball (1), Tennis (1), and football (1).

4.3.2 Procedures.

In order to be eligible for the intervention arm of the study, the participants should have had a frontal plane projection angle (FPPA) higher than 8.4°, during a SLS task in 2D screening (Herrington et al., 2014). The reason that the angle needed to be greater than this was because it reflects high dynamic valgus, which is a result of poor neuromusclar control of the lower limb (Willson and Davis, 2008; Sigward el al., 2012; Ortiz et al., 2016). Thus, it identified female athletes with low neuromuscular control of the lower extremities who might have a high risk of sustaining NCACL injury in the future (Ugalde et al., 2015). The participant's non-dominant side, (supported leg), was the side assessed due to higher incidence of NCACL injuries been reported in female athletes at their non-dominant limb (supportive leg) (Norcross et al., 2010; Brophy et al., 2010; Nilstad et al., 2014; Dawson et al., 2015). The dominant (preferred) leg was defined as the leg used to kick a ball a maximum distance.

4.3.2.1 Screening process: Two-Dimensional (2D) Video capture.

Normal values for 2D video analysis of (FPPA) knee joint while performing variousfunctional tasks such as SLS task have been documented in the literature (Willson and Davis, 2008; Mendonca et al., 2011; Herrington et al., 2014). Several studies showed average values of 8.4±1.8°, 8.0±4.2° and 8.4 ± 5.1° for 2D FPPA knee joint during SLS tasks, respectively. The normative values previously reported by Herrington et al. (2014), were adopted as threshold 2D FPPA values for participants to be included in the current study as this was conducted at the University of Salford in the performance laboratory with similar methods. The participants were briefed through the study and the objectives of the investigations, and the study equipment was explained to them as well. They were then asked to sign the informed consent form and a health history questionnaire which captured demographic information on the participants. At the initial stage of the study, all potential recruits for the study population were screened using 2D analysis. The utilised 2D screening process procedure applied, 2D FPPA data processing, and analysis was previously stated in detailed at Chapter Three section 3.1.3-5.

The average of the three trials was calculated, and if participants recorded an average 2D FPPA greater than 8.4° (>8.4º) (Herrington et al., 2014), they were included in the next stage of the study. For individuals who did not have a 2D FPPA greater than the inclusion criteria, they were thanked for attending the laboratory and informed that they were not eligible for the next stage of the study. The individuals who met the inclusion criteria would be invited to entered into the full study feasibility protocol. Firstly, they were calibrated with the AposTherapy system on attending the laboratory for another session.

4.3.2.2 AposTherapy System calibration.

All participants had their AposTherapy system specifically calibrated by the same senior technician from (AposTherapy, UK) (Figure 4-1a-c) and were required to attend the laboratory for the baseline data collection session soon after these were calibrated. The individuals did not go home with the devices.

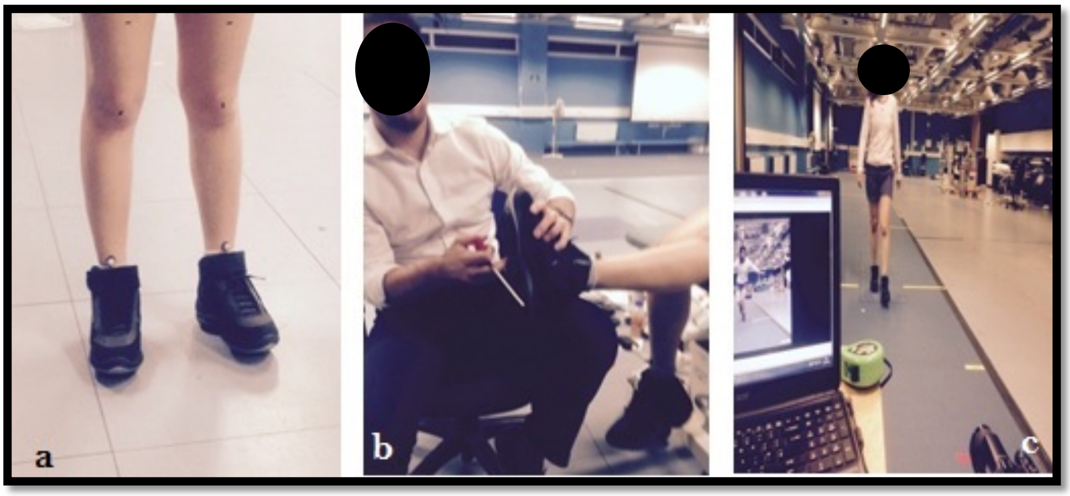


Figure 4- 1: Show the calibration process of the participants.

The AposTherapy system (Figure 4-2) comprises of two modular elements attached onto each footwear platform (Haim et al., 2008, 2010). The elements are attached under the forefoot and hind foot regions of foot platform using two mounting rails which allows for flexible positioning of each element (Haim et al., 2008, 2011). Each element position was calibrated individually to convey specific biomechanical challenges in multiple planes for each participant depending on the calibration from the Apos technician. The exact protocol for the calibration is governed by intellectual property rights of the company and thus for confidentiality reasons this cannot be contained in this thesis. However, the postulated mechanism of the AposTherapy system for reducing the knee valgus loads on the knee joint was influenced with the direction the elements where configuration in particular the once under the forefoot at medial-lateral direction. The manipulation of the element towards the lateral or medial direction, showed the ability to alter the frontal plane loads at the knee joint (Haim et al., 2008).

In addition, the degree of convexity, height and resilience of the elements were choosen to be able to put the participant in a state of perturbation while they are using the AposTherapy system to challenge the neuromuscular control system at lower extremities. Thereby, this is perceived to induce motor adaptation towered the aim to sustain reduced valgus loads during sports manoeuvres. The calibration of the AposTherapy system during this study was not just dependent on the Apos technician subjective assessment he was guided by the visual 2D FPPA of the knee joint.

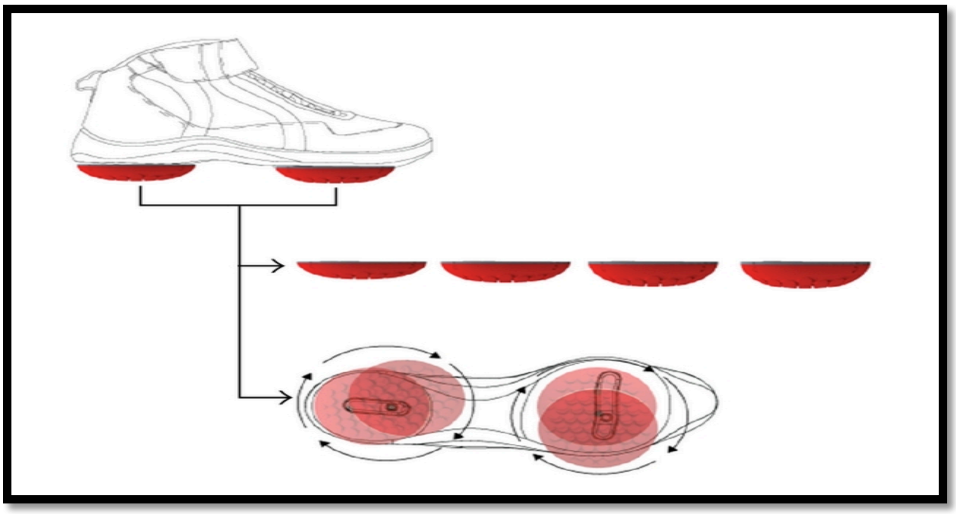


Figure 4- 2: Show the AposTherapy system concept and different levels of convexity elements (Bar-Ziv et al., 2013).

4.3.2.3 Three-dimensional (3D) motion analysis, EMG and CoP-Excursion data capture.

Kinematic data were collected using a 10-camera motion analysis system (Oqus 7, Qualisys AB, Sweden), sampling at 250Hz. Kinetic data were collected using three force platforms embedded into the running tract floor of the lab (AMTI BP 600900, Advanced Mechanical Technology, Inc., USA) sampling at 1500Hz. EMG data was collected from the Vastus Lateralis, Biceps Femoris, Vastus Medialis, and Semitendinosus muscles using a 16 channel Direct Transmission System (Noraxon USA Inc., model 586 TeleMyo DTS Desk Receiver), sampled at 3000Hz synchronized together. For each participant, the non-dominant leg was used for kinematic, kinetic and EMG data collection. The study methods (instrumentation, system calibration, and marker placement) are described in the study methodology in Chapter Three in section 3.2.3.

4.3.3 Study tasks.

The study tasks adopted were the single leg squat (SLS), single leg landing tasks (SLL) and single-leg stance task as described in the study methodology in Chapter Three in section section 3.2.3.3. Each task was completed five times at each testing session.

4.3.4 Conducting the tasks.

4.3.4.1 Baseline data collection session.

Upon arrival to the human performance lab participants were briefed regarding the study and the objectives of the investigations, and the study equipment was explained to them as well. They were then asked to complete and sign the informed consent form and complete the health history questionnaire that included the demographic information of the participants. Prior to the first session, participants wear a comfortable t-shirt and a pair of shorts, they then performed five min of low intensity warm-up stretching. Afterwards, EMG electrodes were placed on the designated muscles of the participants for EMG measurement and completing the collection of MVIC data, the participants followed the same data collection procedures described previously in Chapter Three in section 3.2.3.2.

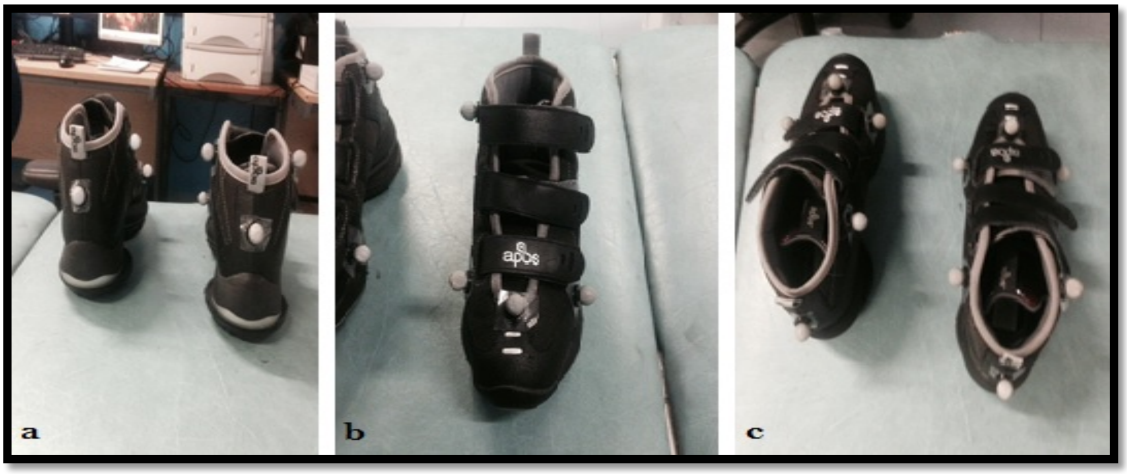


Figure 4- 3: The marker placement on the AposTherapy system.

The participants firstly wore their calibrated the AposTherapy system with markers attached to the head of the first, second and fifth metatarsal, the anatomical landmarks of the feet, and calcaneal tuberosity similar to the placement of standard lab shoes (Figure 4-3 a-c). Before starting the testing, a total of forty markers were attached to the participant's lower limbs as described in the study methodology in Chapter Three in section 3.2.3. After completing the 3D marker placement (anatomical and track markers) (Figure 4-4 a-c).

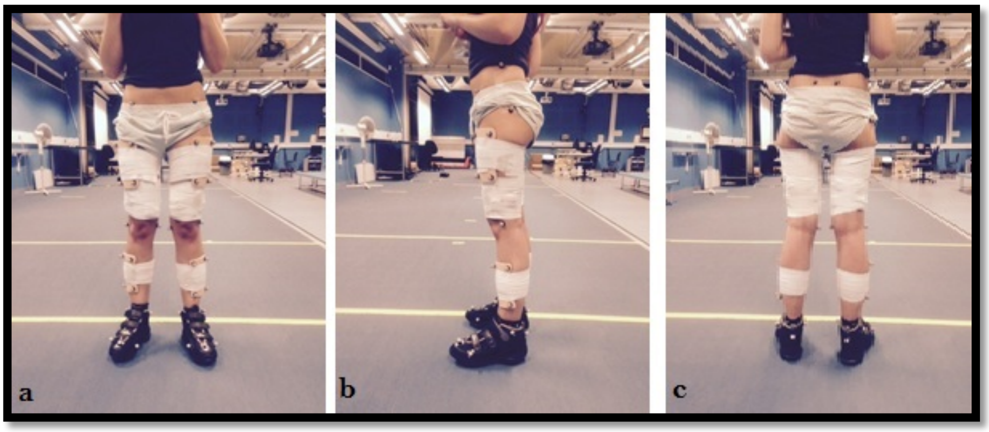


Figure 4- 4: A participant with all markers wearing AposTherapy system.

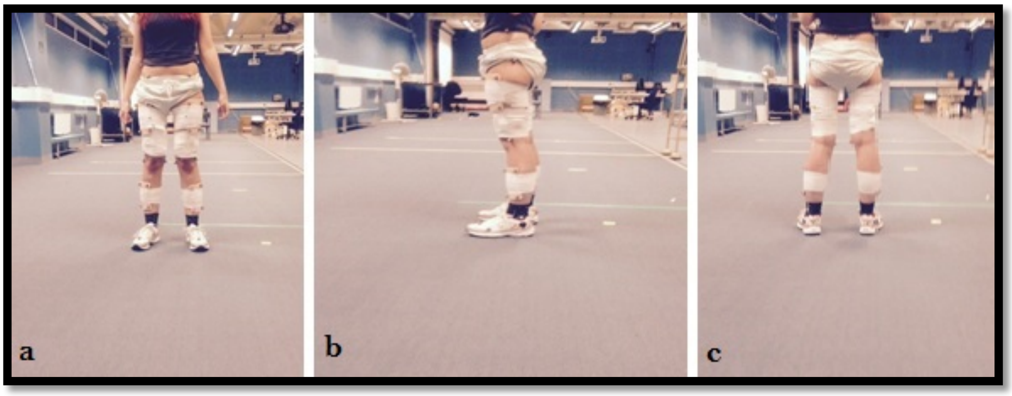


Figure 4- 5: A participant with all markers wearing standard lab shoes.

Each participant was instructed to stand in a stationary position with their arms crossed over their chests to avoid covering any of the markers during the capture of the static trials. Following the completion of the static (standing) trials with the AposTherapy system, all the anatomical markers were removed, only 28 tracking markers kept on (8 markers on both AposTherapy systems lab shoes, 4 markers on the pelvis at ASIS and PSIS both sides, and 16 markers over 4-cluster plates). Participants were instructed to start performing the SLS and Single–Leg Stance tasks while still wearing the AposTherapy system.

For participant's selection of which task to start with (either SLS or Single–Leg Stance task) it was randomly determined by asking each participant to choose one card from the two cards (one for SLS task and one for Single-Leg Stance task). Each participant performed five trials of SLS and Single-Leg Stance tasks as described in Chapter Three section 3.2.3.3. Participants were only asked to do SLS and Single-Leg Stance tasks with the AposTherapy system as it is not recommended to perform landing tasks with them for health and safety reasons (AposTherapy, UK).

After completing the data collection with AposTherapy system each participant was asked to change into standard lab footwear (New Balance, UK) (Figure 4-5 a-c), with all the markers attached to the participant (anatomical and track markers) as described in the study methodology in Chapter Three in section 3.2.3 to perform the static standing trials. Following the completion of the static standing trials with the standard lab footwear all the anatomical markers were removed, only 28 tracking markers kept on (8 markers on both lab shoes, 4 markers on the pelvis at ASIS and PSIS both sides, and 16 markers over 4-cluster plates). Each participant was instructed to perform the SLS Single-Leg Stance and SLL as described in Chapter Three section 3.2.3.3. The selection of which task to start with (either SLS or SLL or Single-Leg Stance tasks) was randomly determined by asking the subject to choose one card from the three cards (one for SLS task, and one for the SLL task and another one for Single-Leg Stance task).

In order to limit systematic bias, participants were given an opportunity to familiarize themselves with the study tasks, prior to performing the tasks. They were requested to practice each task until they felt comfortable with them; which usually took three to four trials until they were confident that they were performing the task correctly. Each participant was instructed to perform it five trials. In addition, they were allowed three minutes' rest between tasks and 30 seconds rest between each trial to limit the fatigue effect on participant performance.

After the baseline data collection session, all the 3D markers and EMG electrodes were removed from the participants. Each participant was given a copy of the training program manual (Table 4-1) and a guideline on how to follow it and how to record his adherence (Appendix Three). The participant was asked to follow the AposTherapy intervention guidelines for the next six weeks.

4.3.4.2 Follow-up data collection session.

On completion of the six-week intervention program, the same objective measures were repeated again and the biomechanical measures that were collected at the baseline session were repeated only wearing the standard lab shoes. All the previously mentioned procedures were followed during the data collection. Each session lasted approximately 90 to 120 minutes.

4.3.5 Study Intervention program.

It is essential to understand the neuromuscular make-up of any exercise element that intervention programs prescribe, as well as the possible ways to modify and adapt exercises component to meet the needs and objectives of the intervention program (Begalle et al., 2012). Therefore, knowledge of the muscular activation pattern during the exercise is vital for establishing the optimum rehabilitation or prevention program to restore muscular integrity and function, which should be the most appropriate for the program objectives (Ucar et al., 2014; Jewiss et al., 2017).

As different types of exercise offer various implications for intervention or rehabilitation program, the once that provides the smallest Quadriceps: Hamstrings (Q:H) activation ratio should be considered better for achieving muscle balance activation pattern which should improve the knee dynamic stability (Begalle et al., 2012; Jewiss et al., 2017), thus, it may be reducing knee valgus motion and loads during high demanding spoerts manovers (Letafatkar et al., 2015 ;Palmieri-Smith et al., 2009). Therefore, if the objective of the prevention or rehabilitation program is to promote more balance muscular activation between the knee extensors and flexors, then the program should incorporate exercises that produce muscle activation of less than 50%-60% MVIC, as higher % MVIC, would result in muscle strength gain and not a neuromuscular adaptation for muscle recrirtment pattern (Begalle et al., 2012).

Thereby, incorporating exercise components that includes quadriceps antagonist might be useful for injury prevention and intervention of an ACL injury. Since it is essential that the quadriceps and hamstring muscles function together in a synchronised manner during the performance of different athletic movements, high load stress levels on the ACL are associated with single-leg support and cutting manoeuvres (Hewett et al., 2005; Myer et al., 2006; Baldon et al., 2012). Moreover, it has been demonstrated that the most balanced (smallest) co-contraction ratio was observed during the following exercises: single-limb deadlift, lateral-band walking exercises, squats (bilateral and/or single), and modified forward lunges when performed in a safe and progressive manner (Yonda et al., 2007; Farrokhi et al., 2008; Ebben et al., 2009). Therefore, it would be logical to presume that it may be beneficial to include these in an exercise program aimed at improving the Q:H action ratio.

Female athletes demonstrated a higher degree of quadriceps activation and lower levels of hamstring muscle activation during running, cutting, jumping and landing during athletic activities when compared to male athletes (Zebis et al., 2009; Zazulak et al., 2005). Therefore, it has been suggested that enhancing the levels of Q:H muscle contraction could be considered one of the primary neuromuscular strategies for providing sufficient dynamic knee stabilisation (Ucar et al., 2014). The Q:H ratio was found to be considerably higher for the OKC (open kinetic chain) exercise than for the ground-based CKC (closed kinetic chain) exercise (Ebben et al., 2009). A typical example is seen in CKC exercise movements when performed on an unstable surface that would challenge knee stability (Irrgang and Neri, 2000; Anderson et al., 2013; Ucar et al., 2014; Kubota et al., 2015).

The CKC exercise is a movement where the distal part is fixed when the sole of the foot makes contact with the ground or exercise equipment (in current study, AposTherapy system). With the distal part fixed, movement at any one joint requires motion at the other joints in the kinetic chain. Thus, the benefit of incorporating CKC exercise may be established by a combination of more muscles being re-programmed to better co-contract together (Kwon et al., 2013). A similar concept was incorporated in study by Gamada et al. (2013), the author reported that performing NMT program while wearing RBS (Realine Blanca shoes) unbalance footwear was effective in inducing a greater muscular activation of the medial hamstring (Semitendinosus) and vastus medialis when performing SLL and DVJ. The same biomechanical adevice in a study by Kubota et al. (2015), the authors also used RBS compare the effectiveness of an NMT program while wearing RBS unbalance footwear and a conventional NMT prevention program. The authors reported no ACL injury in the RBS group while there was one NCACL injury in female participants in the control group (Kubota et al., 2015). The RBS program aimed for correcting dynamic knee valgus and included various types of exercise, such as Bilateral squat, knee bent walk, continuous jumping, single leg jump.

Studies have reported that CKC exercise produces superior eccentric and concentric contraction of the lower limb muscles as well as reducing the shear torque, while adding compressive forces to the joint and improving joint dynamic stability (Balci et al., 2009). Thereby, the majority of NMT program that focus on enhancing dynamic knee stability in female athletes includes exercises that improve Q:H co-contraction (Anderson et al., 2013; Letafatkar et al., 2015). Nonetheless, the majority of ACL injuries occur during CKC activities compared to OKC activities due to the increased muscular control needed to stabilise the knee joint (Dedinsky et al., 2017; Jewiss et al., 2017). Hence, CKC based exercises where chosen to produce adequate balanced Q:H muscle activation during common CKC therapeutic exercises in healthy female lower extremities for the current study intervention exercise program.

The exercise program in the current study (Table 4-1) was developed based on a thorough review of the literature (Caraffa et al., 1996; Myklebust et al., 2003; Chmielewski et al., 2005; Myer et al., 2006; Hurd et al., 2006; Cochrane et al., 2010; Kubota et al., 2015; Letafatkar et al., 2015). The training program was divided into three phases with duration of each phase of two weeks. The goal of the first phase was to introduce simple two-leg tasks, such as a double-legged anterior direction progress exercise. This included a two-leg squat (Figure 4-6 a-b) at first week and then add lateral-band walk exercise (Figure 4-6 e), and two-leg squat while wearing a Thera Band (Figure 4-6 c-b) to increase the challenge. Both exercises were performed for three sets with ten repetitions each session and increased by one set every three days in the phase to reach a maximum of six sets with ten repetitions each.

Table 4-1: illustrated the 6-week study intervention program.

Exercise task	Repetition	1st week	2nd week	3rd week	4th week	5th week	6th week
Two-leg squat	3X10↑to 6X10	x					
Two-leg squat with Threa-Band	3X10↑to 6X10		x				
Single leg squat	3X10↑to 6X10			x	x		
Lateral band walking exercise	3X10↑to 6X10		x				
Forward Lunge	3X10↑to 6X10			x	x		
Single limb dead lift	3X10↑to 6X10					x	x
Static and Walk	60 min/during the day	x	x	x	x	x	x

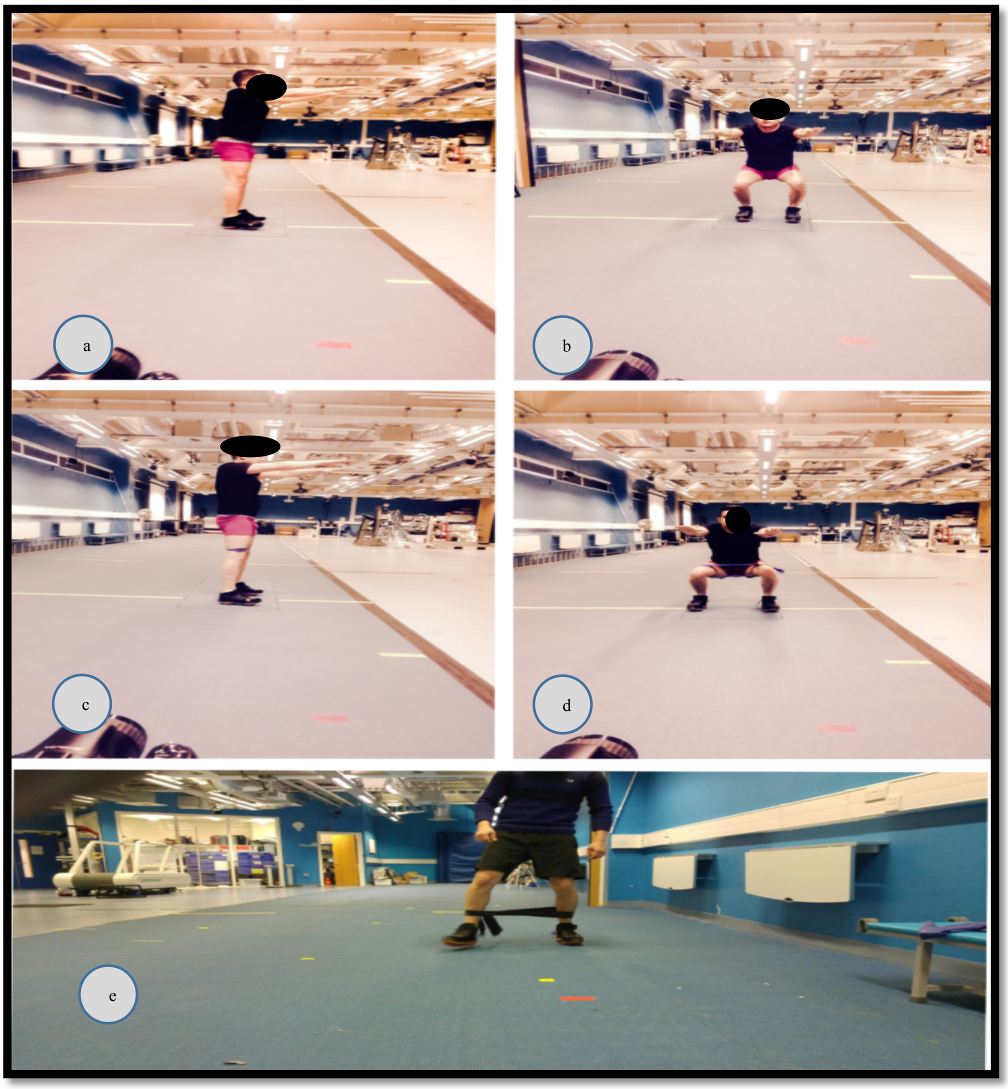


Figure 4-6: Examples of study intervention first phase exercies.

The second phase took place over week three and four of the intervention program. Which included anterior single-leg exercise progression to induce hip and knee joint loads of an increased magnitude during controlled movement with a focus on the deep knee hold position such as a single-leg squat (SLS) (Figure 4-7 a-b) and forward lunge (Figure 4-7 c-d). This would demand adequate torque generation and attenuation of the proximal musculature to control the plane of motion at the hip.

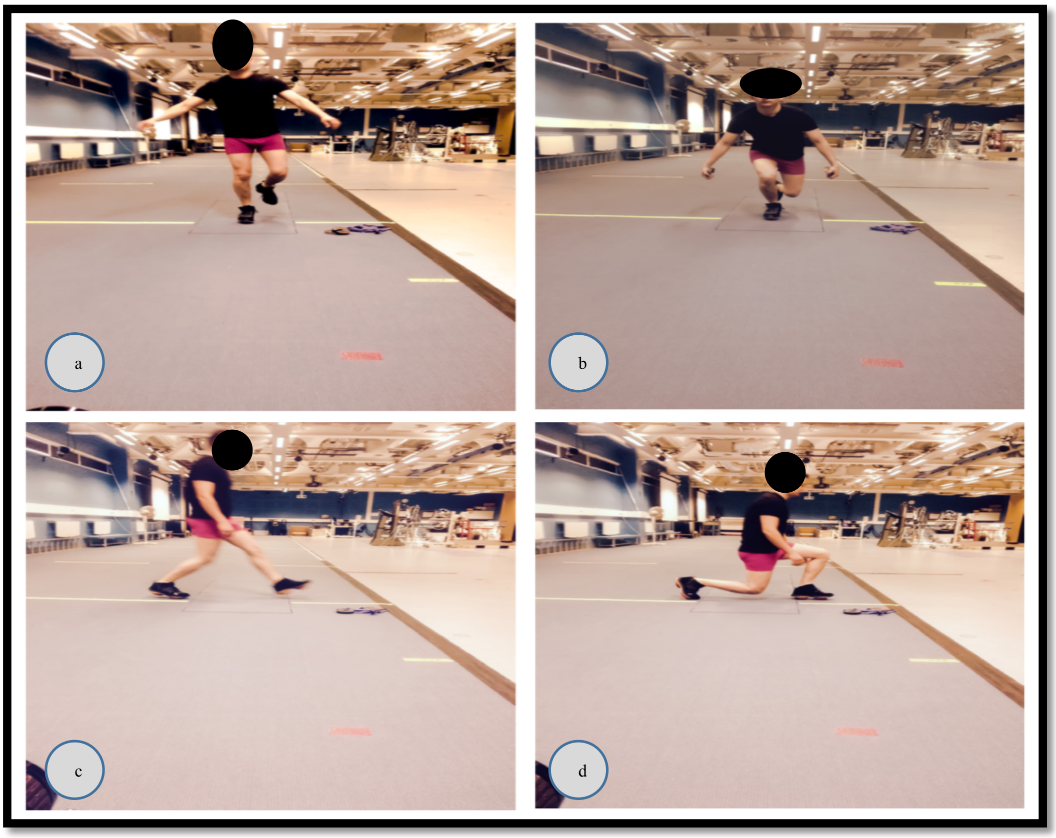


Figure 4-7: Examples of study intervention second phase exercise.

The participants were instructed to start doing three set with ten repetitions each session and increased by a set every three days in the phase to reach a maximum of six sets with ten repetitions each. The participants were instructed to perform SLS at no higher than 90° or less than 30°. Performing a single-leg squat at more than 90° may favour the quadriceps due to the increase in external torque, but if the single-leg squat goes below 30° this would not allow optimal action for the hamstrings since the moment arm of the hamstrings is greater from 50 to 90° of knee flexion (Dedinsky et al., 2017).

The final phase of the intervention program covers the last two weeks of the six-week intervention program, which includes the single-leg deadlift exercise (Figure 4-11 a-c). The key component is to minimise trunk deviation in the frontal and transverse planes while improving co-contraction of the quadriceps and hamstrings. The participants were instructed to keep the muscles of the standing leg relaxed with the knee flexed slightly and foot relaxed. The exercises started with three set of ten repetitions each session and increased gradually till they reach a maximum of six sets with ten repetitions each as previously phases. The goal of the exercise is control of the frontal plane to execute proper technique.

Figure 4-8: Examples of study intervention third phase exercise.

The intervention program was conducted on a daily basis. The initial exercise involved both legs to safely introduce the participants to the training movements, and then a greater number of single leg movements were progressively introduced. Both the intensity and the difficulty of the training drills were advanced in a systematic manner. In addition, participants were instructed to wear the AposTherapy system for a minimum of 60 minutes during the day while performing their daily activities at home and they were allowed to wear their AposTherapy system even outside their homes after the first two weeks of the study intervention program. The participants were required to finish two thirds of the intervention training sessions (Myer et al., 2005, 2006; Anderssion et al., 2013; Sugimoto et al., 2014) to be included in the study.

4.4 Data processing.

4.4.1 3D data.

The data processing methods previously descripted in section 3.2.4.1 of Chapter Three were used.

4.4.2 Electromyography data.

The data processing methods previously described in section 3.2.4.2 of Chapter Three were also used.

4.4.3 Centre of Force Pressure (CoP) Excursion data.

The data processing methods previously described in section 3.2.4.3 of Chapter Three were also used.

4.5 Data analysis.

The descriptive statistics included Mean ± standard deviation for all measured variables was calculated. No formal statistics were undertaken due to the small sample size in the feasibility study.

4.6 Results.

Five recreational active females from the staff and student population from the University of Salford (aged 27.8 ± 3.1 years, mass 55.8 ± 8.4kg, and height 163.6±3.6cm) were successfully recruited from 13 participants. All participants were recreationally active, were the participant's physical activity levels assessed according to Tegner activity scale (TAS) (Tegner et al., 1985) were 5.6. They participated in the study after being 2D video screened showing high using 2D FPPA (14.7 ± 5.6°). Four of the participants were right leg dominant, and only one was left leg dominant. In addition, the participant's Adhernet rate was more than 90% of the study intervention program.

4.6.1 3D data.

There were no major changes in the peak kinematic of kinetic parameters following the AposTherapy intervention. The kinematic and kinetic outcomes highlighted in Table 4-2, & Table 4-3.

Table 4 –2: Mean ±SD and mean difference between pre- and post-AposTherapy intervention results during SLL Task.

Variables	SLL Baseline (Mean±SD)	SLL 6-week (Mean ±SD)	Mean diff ±SD	SEM	MDD
Knee valgus angle (°)	-8.05±2.8	-7.01±3.19	1.04±1.01	0.84	2.30
Knee valgus moment (Nm/kg)	0.26±0.13	0.22±0.14	0.04±0.18	0.05	0.14
Knee flexion angle (°)	70.8±10.07	72.59±4.11	1.71±12.48	1.16	3.13
Knee Flexion moment (Nm/kg)	1.90±0.19	1.78±0.32	0.12±0.28	0.15	0.41
Hip Add angle (°)	5.42±5.11	6.7±6.13	1.28±1.36	2.27	6.12
Hip Adduction moment (Nm/kg)	1.09±0.23	1.03±0.35	0.06±0.23	0.10	0.27
GRF(∗BW)	2.34±0.40	2.02±0.6	0.32±0.86	0.17	0.46

Single legged landing (SLL), Standard deviation (SD), Ground reaction force (GRF), Mean difference (Mean diff).

Table 4 – 3: Mean ±SD, mean different between pre- and post-AposTherapy intervention results during SLS Task.

Variables	SLS Pre (Mean ±SD)	SLS Post (Mean ±SD)	Mean diff± SD	SEM	MDD
Knee valgus angle (°)	-3.96±1.54	-4.01±2.43	0.5±2.15	0.94	2.53
Knee valgus moment (Nm/kg)	0.206±0.19	0.212±0.20	0.01±0.03	0.02	0.05
Knee flexion angle (°)	75.8±3.8	74.4±5.1	1.4±5.6	1.75	4.73
Knee Flexion moment (Nm/kg)	1.57±0.07	1.47±0.15	0.09±0.18	0.06	0.16
Hip Adduction angle (°)	11.13±6.74	10.47±7.3	0.66±1.79	2.28	6.21
Hip Adduction moment (Nm/kg)	1.09±0.13	1.10±0.56	0.01±0.52	0.07	0.19
GRF(∗BW)	1.16±0.08	1.12±0.14	0.04±0.08	0.02	0.05

Single legged squat (SLS), Standard deviation (SD), Ground reaction force (GRF), Mean difference (Mean diff).

4.6.2 Electromyography data.

The Electromyography EMG data during both SLL and SLS dynamic tasks are presented in Table 4-4, Table 4-5, Table 4-6, Table 4-7. The results highlighted that whilst there were changes in the co-contraction index these were not large differences.

Table 4 –4: Mean ±SD %MVIC EMG pre- and post-AposTherapy intervention, and mean difference during SLS Task.

Variable	SLS Pre (Mean ±SD)	SLS Post (Mean ±SD)	Mean diff ±SD	SEM	MDD
Vastus Medialis –Semitendinosus (VM-ST) CCI (% MVIC)	86.6±46.34	97.4±83.34	16.8±35.86	4.67	12.95
Vastus Lateralis- Biceps Femoris (VL-BF) CCI (% MVIC)	80.8±59.2	64.6±42.98	16.2±27.17	4.02	11.14
Med (VM-ST) to Lat (VL-BF) ratio	1.18±0.56	1.53±0.95	0.34±1.24	0.11	0.29

Single legged squat (SLS), Standard deviation (SD), Vastus Medialis and Semitendinosus (VM-ST), Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index (CCI).

Table 4 –5: CCI values during feed-forward and feed-back phases Mean ±SD MVC % pre- and post-AposTherapy intervention, and mean difference during SLL Task.

Variable	Test	SLL Task phases	Mean ±SD (% MVIC)	SEM	MDD
VM-ST CCI	Pre-AposTherapy Baseline	Feed-forward phase	49.4±24.2		
		Feed-back phase	83.0±38.58		
	Post – AposTherapy 6-weeks	Feed-forward phase	60.4±32.48	3.59	9.95
		Feed-back phase	63.8±43.55	4.84	13.41
VL-BF CCI	Pre-AposTherapy Baseline	Feed-forward phase	67.4±22.7		
		Feed-back phase	79.4±45.21		
	Post – AposTherapy 6-week	Feed-forward phase	81.6±49.32	5.52	15.3
		Feed-back phase	76.6±46.54	4.30	11.91

Single legged landing (SLL), Standard deviation (SD), Vastus Medialis and Semitendinosus (VM-ST), Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index (CCI).

Table 4 –6: Mean ±SD pre- and post-intervention medial (VM-ST) to lateral (VL-BF) muscular co-contraction ratio, and mean difference for SLL task during Pre and Post-landing (Feedforward and Feedback) phase.

Variable	Baseline (Mean ±SD)	6-weeks (Mean ±SD)	Mean diff± SD	SEM	MDD
Med (VM-ST) to Lat (VL-BF) ratio (Feedforward phase) during SLL task	0.75±1.37	1.38±1.5	0.61±1.7	0.10	0.28
Med (VM-ST) to Lat (VL-BF) ratio (feedback phase) during SLL task	1.28±0.63	1.15±0.91	0.12±1.25	0.17	0.46

Single legged landing (SLL), Standard deviation (SD), Med (Medial side of knee), Lat (Lateral side of knee), Vastus Medialis- Semitendinosus (VM-ST), Vastus Lateralis- Biceps Femoris (VL-BF), Mean difference (Mean diff).

Table 4 –7: Mean± SD and mean difference for the medial (VM-ST) to lateral (VL-BF) co-contraction index ration during SLS task for pretest assessment while waring Lab control footwear and AposTherapy system.

EMG variables	SLS control lab shoe (Mean ±SD)	SLS AposTherapy (Mean ±SD)	Mean diff ±SD	SEM	MDD
VM-ST CCI (% MVIC)	80.6±48.34	75.0±54.11	5.60±15.30	4.67	12.95
VL-BF CCI (% MVIC)	80.8±59.20	42.40±33.23	38.40±32.79	4.02	11.14
Medial to Lateral ratio	1.18±0.56	1.96±0.92	0.77±1.02	0.10	0.29

Single legged squat (SLS), Standard deviation (SD), Vastus Medialis and Semitendinosus (VM-ST), Vastus Lateralis and Biceps Femoris (VL-BF), co-contraction index (CCI) and Mean difference (Mean diff).

4.6.3 Centre of pressure excursion (CoP-Excursion) data.

4.6.3.1 CoP-Excursion of control shoes and AposTherapy.

The immediate difference in CoP-Excursion when wearing the AposTherapy system (Mean difference ±SD: 69.80±56.50 mm), showed a large increase in the range of motion for CoP-Excursion in comparison with that of the control shoes Table 4-8.

Table 4 –8: Mean ±SD and mean difference for CoP-Excursion between control lab shoe and AposTherapy device.

Condition	Mean± SD mm	Mean difference ±SD mm	SEM	MDD
Control shoes	24.6±4.77	69.8±56.5	4.0	11.12
AposTherapy	94.0±53.98			

4.6.3.2 CoP-Excursion of pre-post AposTherapy Intervention.

After wearing the AposTherapy device, there were small changes (5.0±12.38mm Mean difference ±SD), in the range of motion for CoP-Excursion in comparison to the baseline values Table 4-9.

Table 4 –9: Mean ±SD for CoP-Excursion for pre &post-test.

Condition	Mean ±SD mm	Mean difference ±SD mm	SEM	MDD
Pre-AposTherapy Baseline	24.6±4.77	5.0±12.38	4.0	11.12
Post-AposTherapy 6-weeks	19.6±7.50			

4.7 Discussion.

The purpose of this feasibility study was two-fold: firstly, to assess the feasibility of running a six-week intervention program with the AposTherapy intervention; secondly, to observe any alterations in the biomechanical and muscle activity parameters over this duration. This is the first study to embark on such a project: looking at the ACL injury associated factors in non-injured athletic individuals. It has been documented that small studies, with all the trappings of major studies such as hypothesis testing, randomisation, and study methodology, could be labelled as a feasibility because it does not have the power to test a clinically meaningful hypothesis (Bugge et al., 2013; Shanyinde et al., 2011; Arain et al., 2010).

Feasibility assessment

Feasibility studies are used to determine the important methodology that is required to design the main study such as follow-up rates, the response rates for recruitment methods, and compliance rates. Moreover, feasibility studies do not evaluate the results of interest; this is left to the main study (Bugge et al., 2013; Arain et al., 2010). Thereby, the feasibility study should resemble the main study in many respects (Eldridge et al., 2016; Teare et al., 2014). This preliminary study focuses on the processes of the planned main study, for example, to ensure recruitment, randomisation, safety and practicability of the intervention program, follow up, and compliance rate all run smoothly (Teare et al., 2014; Leon et al., 2011; Arain et al., 2010; Farbu et al., 2007). The methodology outcomes were recorded separately for: acceptability of the intervention to participants, compliance to intervention, recruitment, and logistics of the multi-centre procedure. Other aspects of the intervention such as lab time, outcome assessment, procedure, and efficacy are of major benefit to the intervention program.

The use of recruitment posters appeared to be insufficient for recruitment participants. Thereby, the main researcher adopted a more direct approach method for reaching university students and employees involving approaching groups of students prior to or at the end of their lectures, tutorials and lab session by giving briefly group description of the study aim, procedures, and criteria and handing them the recruitment posters, which was a much more successful method to recruit participants as it was more engaging and interesting for potential participants. The recruitment rate was reasonable where on average one of every four females approached were interested in participating in the study. The 2D video analysis using FPPA of the knee joint was a suitable and efficient procedure to quickly screen the participants and was convenient for most potential participants. Moreover, when screening the participants using 2D analysis, an average of one from every two potential participants showed high 2D FPPA and were considered for inclusion in the study. In addition, after the recruitment of every four to five participants, their shoe sizes were sent to Apos UK headquarter in London to arrange for their shoes to be sent to the university performance lab.

One of the major logistical challenges in this study was that this was dependent on access to an AposTherapy calibration clinician. This involved arranging with Apos UK to provide the AposTherapy system with the required sizes and also to send the same specialised physiotherapist for calibration. The availability of funding to provide an AposTherapy system and physiotherapist was likely to impact on the decision of the study design and sample size. The intervention is very expensive and thus communication will be essential with the company to ensure an efficient study can be undertaken. Therefore, this sample size has been decided pragmatically considering the available resources.

Regarding the calibration session, it was proposed the best way to do it would be on a group basis. Considering the calibration was done by the same specially qualified physiotherapist from Apos UK, who is located in London, it was considered more efficient and convenient to conduct group calibration for every three to four participants in the university human performance laboratory. Another issue was observed was the calibration method, as this was the first time the AposTherapy system was applied as an intervention to reduce frontal plane knee joint valgus motion. Therefore, 2D video analysis was used during the calibration to aid the physiotherapist in the calibration process. Moreover, the time required to perform the 2D video analysis on FPPA for the supportive knee took approximately 15 to 20 minutes for each potential participant, whereas the calibration ranged between 30 to 40 minutes for each participant, which was acceptable by the participants. However, this was much longer than anticipated and needed to be considered for the main study. Furthermore, each assessment session ranged between 90 to 120 minutes, which was considered acceptable by the participants.

In regards to the training program Table 4-1 that was to be performed while wearing the ApoSTherapy system, the progressive manner and the nature of the exercise was acceptable to the participants. However, the participants commented that it took more than 15 minutes to perform the program and that sometimes they could not do all the walking trials. However, the compliance rate was more than 90% (number of sessions and session duration), with no dropout was reported. The adherence of the participants to the study intervention program was monitored by using participant's follow-up sheet (Appendix three), which was handed to each participant at the beginning of the study.

The important issues addressed in the feasibility study included the safe use of the ApoSTherapy system while wearing it and performing the prescribed exercises during the study period. There were no reported injuries or complaints brought to our attention. The only issue was muscle soreness during the first week of the intervention program which wore off as the participant adapted to the study intervention program; this was explained to all participants before the start of the intervention program. The feasibility study focused on examining the data collection procedures, follow up and dropout rate, and acceptability. In addition, the training program components were reviewed in regard to efficiency and safety (Teare et al., 2014; Bugge et al., 2013; Thabane et al., 2010). Additionally, the whole feasibility trial and overall design were considered in regard to clinical outcomes including feasibility/acceptability of intervention and the efficacy and safety of the intervention (Bugge et al., 2013; Leon et al., 2011; Arain et al., 2010).

Kinematic, kinetic, EMG and Postural stability parameters

Postural stability data

The initial outcomes of the feasibility study might suggest the ability of the ApoSTherapy system to greatly destabilise the lower limb and increase postural instability. When comparing MDD values previously reported in reliability study in Chapter Three in section 3.2.7.4 with the values observed instantly after wearing ApoSTherapy system Table 4-8. Yet, in a controlled manner this was considered a primary component to affect muscle recruitment patterns. This was demonstrated in the change in the CoP-excursion as soon as the individuals wore the devices that theoretically would destabilise the individual and help neuromuscular function. Many studies reported improvement in postural stability measures after using unstable biomechanical devices such as (e.g. Reebok Easy Tone) or rocker-bottom (e.g. Masai Barefoot Technology) (Plom et al., 2014; Price et al., 2013; Landry et al., 2010; Zech et al., 2010; Nigg et al., 2006). When standing upright, the body's centre of mass is continuously in motion (Farzali et al. 2017; Horsak et al., 2013), it is thought that changes in muscle control may be reflected in the alteration in the direction of the CoP trajectories (Farzadi et al., 2017; Elkjaer et al., 2011; Landry et al., 2010). Thus, this may reflect an alteration in motor response as result of neuromuscular control adaption (Lehmann et al., 2017; Negahban et al., 2014; Zech et al., 2010) Furthermore, in this feasibility study we also observed similar outcomes as a considerable increase in the CoP-excursion was observed, when using AposTherapy system.

Kinematic and kinetic data

In regards to the kinematic and kinetic data, there were small changes during the functional tasks. There was small reduction in the knee valgus motion and moment during the SLL task in comparison to their baseline values. Interestingly, the knee valgus angle values drop at post-test to levels exceed SEM values Table 4-2 previously reported in reliability study in Chapter Three in section 3.2.7.2. While during SLS task the knee valgus motion and moments showed very minimal changes, which may be reflective of the nature of the SLS task, as this is less demanding than landing tasks (Ortiz et al., 2010). However, there was a reduction in the GRF during both study tasks. The GRF values shown at post-test during SLS task drop in degree more than SEM values Table 4-3 previously reported in reliability study in Chapter Three in section 3.2.7.2. This may be a promising observation as high GRF in considered one of risk factors for many musculoskeletal injuries of the lower limb particularly ACL (Bates et al., 2015; Zahradnik et al., 2015).

EMG data

From a neuromuscular perspective, there were changes observed at post-test during the SLS and SLL tasks. During SLS task the medial knee muscular co-contraction index was increased, whereas, the lateral knee muscular co-contraction index showed reduction. Both values observed were higher than MDD values Table 4-4 previously reported in reliability study in Chapter Three in section 3.2.7.3. This results in improvements at medial to lateral knee muscular co-contraction ratio during the SLS task with values higher the MDD Table 4-

4 previously reported in reliability study in Chapter Three in section 3.2.7.3. Moreover, the medial knee muscular co-contraction at pre-landing phase during SLL task showed improvement higher than MDD values Table 4-6 previously reported in reliability study in Chapter Three in section 3.2.7.3. The decrease in the medial to lateral knee muscle co-contraction ration has been documented as a high risk muscle recruitment pattern for ACL injury (Palmieri –Smith et al., 2008). Thereby, the observed improvement in the medial to lateral knee muscle co-contraction ration in this feasibility study after the participation in the study intervention may had indicate a positive neuromuscular adaptation achieved.

Nevertheless, there was instant improvement in the medial to lateral knee muscular co-contraction ration when the AposTherapy system was worn, in comparison to controlled lab shoes. These outcomes were similar to the instant changes in the medial to lateral knee muscular co-contraction index reported in study by Andersson et al. (2013), the author reported instant changed in neuromuscular recruitment pattern while standing on the unstable device while performing a single leg squat (SLS) task. Knee joint passive resistance to dynamic knee valgus could be limited by reduction in medical knee joint compression (Hewett et al., 2005; Letafatkar et al., 2015; Zebis et al., 2016). The increase of lateral flexors muscle activity combined with low ratio of medial to lateral extensor recruitment may compress the lateral side of the knee joint and lift-off at medial joint which directly stress the ACL (Sell et al., 2006; Hewett et al., 2005; Rozzi et al., 1999; Markolf et al., 1995).

A typical example is closed kinetic chain movement performed on unstable surface with challenge knee joint stability and, thus enhance quadriceps-hamstrings co-contraction (Irrgang and Neri, 2000; Zebis et al., 2008, 2011). Moreover, a few have implanted similar exercise and demonstrated a success in changing knee kinematics in female athletes during jump tasks (Lephart et al., 2005; Myer et al., 2006; Zebis et al., 2008; Letafatkar et al., 2015).The concept of employing of ACL injury intervention prevention program that target the development of motor program characterized by improving muscle activity coordination by incorporate perturbation training, might be more successful or at less slimier to typical other NMT program which implemented jumping focused training program (Cochrane et al., 2010; Zebis et al., 2008; Myer et al., 2006; Myklebust et al., 2003; Caraffa et al., 1996).

Perturbation training involves maintaining lower limb balance during the control destabilization of support surface (Hurd et al., 2006). In current study participants had shown increase in co-contraction index in VM-ST muscle in particular in feedforward motor control phase. The low co-contraction in the medial portion of the muscle surround the knee joint may predispose the knee joint to excessive valgus position that could put ACL in high risk of rupture (Palmieri –Smith et al., 2008, 2009). Several NMT programs have successfully implement unstable training device to compensate for the missing training affects, by improving knee and ankle proprioception and strength (Letafatkar et al., 2015; Goryachev et al., 2011; Nigg et al., 2006; Waddington et al., 2004; Waddington et al., 2000).

An intervention program must be feasible and practical at same time in terms of their applicability to younger population of athletes to insure compliance which is vital. Furthermore, its believed that young athletes are more likely to be compliant when the prevention training requires little additional time on the athlete's behalf, the advantage of incorporate intervention program which require little additional time on the athletes (Mandelbaum et al., 2005; Steffen et al., 2008; Sugimoto et al., 2014). The incorporation of the AposTherapy intervention in recreational female athletes with a risk of NCACL injury during sport activities could be a compelling concept as it seems to be an attractive design because of its feasibility, simplicity, and promising effectiveness. The outcomes of this feasibility study were promising but not conclusive because of the lack of sufficient participant's sample size. Therefore, a larger study would be recommended. The most appropriate design would be a study that has three study groups, AposTherapy system with exercise group similar to the once applied in this feasibility study, AposTherapy system without exercise group, who will only use the device during walking while doing daily activities and a study group receiving no treatment at all, who would continue their normal routine with no changes to be considered as the study control group.

The results of this study may be subject to a number of limitations. It needs to be acknowledged the intellectual property rights for the calibration protocol of the AposTherapy system prevented the detailing in the current study. In addition, this study outcome has limited generalisability as the relationship were only observed in healthy uninjured recreational female athletes.

4.8 Conclusion.

The study has determined that performing an intervention with the AposTherapy system is feasible. The AposTherapy system demonstrated it can have an influence on the CoP trajectories after using the AposTherapy system. In addition, there were changes in knee valgus motion and moment during landing along with reductions in GRF and improvements in muscular recruitment pattern. However, this must be taken with caution due to the non-statistical testing adopted in this feasibility study and also whether the exercise program alone, rather than the AposTherapy system was responsible which needs to be assessed. Nevertheless, the additional effect of the exercise component needs to be investigated without the AposTherapy system. However, this would be beyond the scope of the present thesis.

Chapter Five: The role of incorporating AposTherapy System on lower limb biomechanics in recreational female athletes with potential high risk for non-contact ACL Injury-Intervention study

5.1 Introduction.

In the previous chapter it was demonstrated that it is feasible to undertake a study involving the AposTherapy intervention in individuals who are healthy, but showing a risk factor for an ACL injury due to their high dynamic valgus. In that study, a small number of female participants were assessed before and after a six-week intervention program. The feasibility study in Chapter Four showed some promising observations as there were instant increases in the participant's instability while wearing the AposTherapy system compared with wearing the lab control shoes. Moreover, there was a trend towards an improvement in postural stability and muscular recruitment pattern and reduction in knee valgus loads. In addition, the study demonstrated the feasibility to use the AposTherapy system in future intervention programs. However, there were some major limitations to the previous feasibility study in that there was no study control group, which could have meant that the training program itself may have been the difference rather than the unstable footwear device.

The individual effect of using the AposTherapy system alone is still unknown, to determine if using the device without the extra training elements of exercise in the training program has an effect on biomechanical and muscle activation patterns. Therefore, a larger study with an appropriate control group would be the next step to examine whether the AposTherapy system has a better effect than a control group. Secondly, it was understood from the feasibility study that it was problematic for the participants to exercise with the AposTherapy system coupled with other exercise elements, and therefore, it was deemed logical to adopt the approach that is undertaken by knee osteoarthritis patients where they would just perform daily activities with the intervention (Haim et al., 2010; Elbaz et al., 2013).

However, in order to see if the AposTherapy system has any effect on the biomechanical and neuromuscular aspects in the individuals a comparison study should be undertaken. Therefore, a comparison study was conducted and this chapter presents the detailed outcomes, whereby the AposTherapy system had an exercise program intervention group included, and another group that only had the device and walked and performed activities of daily living with the device, beside a control group.

5.2 Research question and hypothesis.

The research question was whether the AposTherapy intervention would alter the lower limb biomechanical alignment following a six-week intervention period (The first intervention with just using the AposTherapy system when walking only for 60 minutes on a daily basis inside and outside the house. The second intervention was similar to the one followed in the feasibility study at chapter four were the AposTherapy system used during walking plus exercise regime while wearing the device) in individuals with poor neuromuscular control. It was hypothesized that the AposTherapy system would improve neuromuscular control of the lower limb in female participants, reflecting by showing improvement in their biomechanics parameters by reducing knee valgus angle, knee valgus moments, and better medial to lateral knee joint muscle co-contraction ratio activity. In addition, to enhancing the postural stability. Therefore, the specific null hypothesis are as follows:

- Hypothesis 1: There is no significant difference in total postural stability before and after the AposTherapy intervention and between the groups during Single leg stance task.
- Hypothesis 2: There is no significant difference in maximum knee valgus angle before and after the AposTherapy intervention and between the groups during Single leg squat task (SLS) and Single leg landing task (SLL).
- Hypothesis 3: There is no significant difference in maximum knee valgus moments before and after the AposTherapy intervention and between the groups during Single leg squat task (SLS) and Single leg landing task (SLL).
  Hypothesis 4: There is no significant difference in muscle co-contraction of medial side of the knee (Vastus Medialis & Semitendinosus) before and after the AposTherapy intervention and between the groups during Single leg squat tasks (SLS) and Single leg landing tasks (SLL).
- Hypothesis 5: There is no significant difference in muscle co-contraction of lateral side of the knee (Vastus Lateralis & Biceps Femoris) angle before and after the AposTherapy intervention and between the groups during Single leg squat tasks (SLS) and Single leg landing tasks (SLL).

5.3 Method.

This was a pilot parallel group randomised controlled trial (Pilot RCT) study. The same inclusion and exclusion criteria which were previously stated at Chapter Three in section 3.2.2.1. However, the study population had three study groups: the first group, were considered as a control group they will do only their usual training regime; the second study group, participants performed AposTherapy intervention which would be similar to the one applied in the feasibility study at Chapter Four in section 4.3.5, where the participant would be wearing the AposTherapy system during walking beside performing certain exercise while wearing the AposTherapy system according to the training program instructions; the third group, were only using the AposTherapy system during walking for 60 min period each day according to the standard intervention program instructions for other individuals treated with the AposTherapy system. All groups were seen for a post-test assessment after six weeks from the pre-testing. Written informed consent was attained from all participants, and research Ethics Committee of University of Salford approved this intervention study (HSCR 13/69).

5.3.1 Participant.

Seventy-one female recreationally active staff and students were recruited from the University of Salford via poster. After they potential participants were 2D video screened (2D FPPA:10.43±1.92°) there were forty-two potential participants showing a high dynamic valgus for their non-dominant knee All participants were randomly allocated (www.randomization.com) (Kim et al., 2014) to each of the three study groups after they were explained about the nature and protocol of this study. Three participants withdrew before having the calibration session due to scheduling conflicts, and four participants could not continue and attend the baseline assessment due to travelling commitments which caused scheduling conflicts.

During the intervention period two participants had to withdraw because they sustained a knee and an ankle injury during sport participation. One individual was excluded at the end of the study intervention as she did not manage to complete the minimum adherence rate (number of sessions and session duration) of the intervention which was 75% of the study intervention. Thirty-two participants managed to complete the study intervention in all groups, where they managed to achieve an adherence levels higher than 75% (88% for the walking group and 81% for the walking and exercise group).

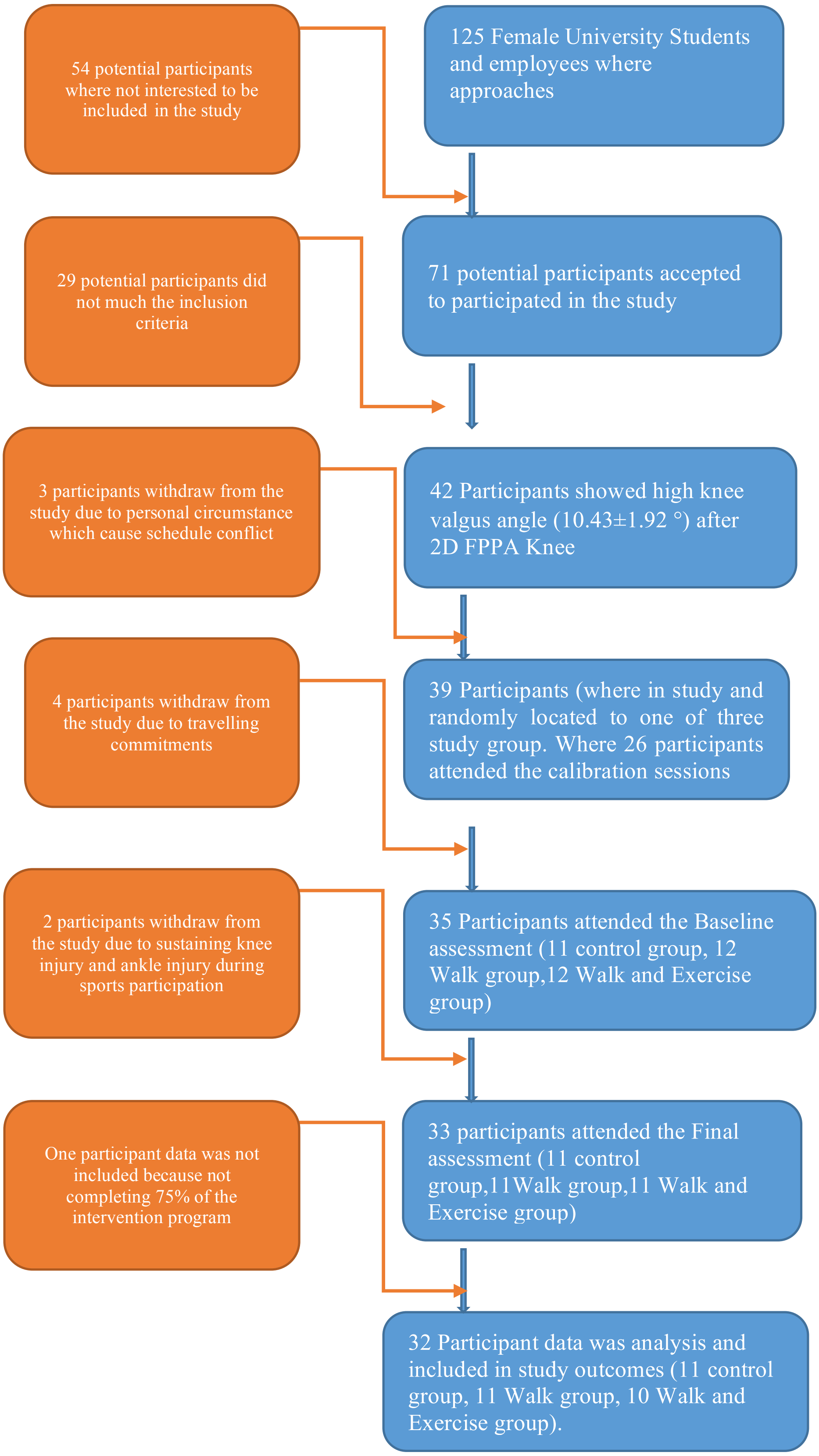
The sample size of the study was estimated to be 33 for each of three study groups using G power software (Gpower3.1) (Faul et al., 2009). A-priori required sample size given (α=0.05), power (1-β) 0.95, and effect size (0.25) was calculated. The main study sample size would be 99 participants. However, considering the the nature of the thesis study limited funding and time restriction was likely to impact on the number of the participants recruited. With the Apostherapy system being an expensive equipment and the time availability of Apos technician. Therefore, this sample size has been decided pragmatically considering the available resources.

There were 11 participants in the control group (cont gp) 10 participants in the walking group (Walk gp) and 11 in the walking exercise group (WE gp) (Table 5-1). No statistical differences were found amongst the three study groups at pre-post-test assessment sessions regarding participant's height, mass and age (p=0.65, p=0.26, and p=0.16, respectively). In addition, there was no significant differences between groups in the participant's physical activity levels (p= 0.8). Tegner activity level scale (TAS) (Tegner et al., 1985) for the walking group and walking and exercise group were 5.7 and 5.8, respectively. In regarding the 2D FPPA scores there was no significant differences between groups at the screening session (p=0.6). Participants sports activities included basketball (4), football (3), hockey (2), netball (8), rugby (2), squash (1), volleyball (3), handball (2), tennis (2), cheerleading (1), contemporary dance (1), rowing (1), martial arts (1) and skiing (1).

Table 5- 1: Participants demographic data in Mean ±SD.

Parameters	Control group	Walk group	Walk Exercise group
Height	165.9±4.1 cm	167.0±3.19 cm	165.6±3.2 cm
Mass	63.8±4.08 kg	66.2± 5.11 kg	63.5± 4.15 kg
Age	24.5±5.47 years	26.5±3.69 years	28.0±3.67 years

Figure 5-1: Main study recruitment and progress flow char.



5.3.2 Procedures.

5.3.2.1 Screening process: Two-Dimensional (2D) video capture.

The same study protocol for the screening process with 2D video capture, using 2D FPPA which would identify individuals with high dynamic valgus (Willson and Davis, 2008; Sigward et al., 2011; Ortiz et al., 2016; Herrington et al., 2017). The same method which was conducted in the feasibility study in section 4.3.2.1 of Chapter Four, was undertaken to identify individuals. The participants non-dominant side (supported leg), was the side assessed due to higher incidence of NCACL injuries been reported in female athletes at their non-dominant limb (supportive leg) (Norcross et al., 2010; Brophy et al., 2010; Nilstad et al., 2014; Dawson et al., 2015). The dominant (preferred) leg was defined as the leg used to kick a ball a maximum distance.

5.3.2.2 AposTherapy system calibration.

The AposTherapy calibration, which was conducted in feasibility study in section 4.3.2.2 of Chapter Four, was undertaken in the same manner whereby the key targets were a reduction in knee valgus frontal plane motion.

5.3.2.3 Three-dimensional (3D) motion analysis, EMG and CoP-Excursion data capture.

Participants followed the same collection procedure described previously in section 3.2.3 of Chapter Three, on the collection of the 3D, EMG and CoP-excursion measures.

5.3.3 Study tasks.

The study tasks adopted were the same as the feasibility study with the single leg squat (SLS), single leg landing tasks (SLL) and single-leg stance task as described at in section 3.2.3.3 of Chapter Three. Each task was completed five times at each testing session.

5.3.4 Conducting the tests.

5.3.4.1 Baseline data collection session.

All individuals were required to attend the human performance laboratory for the initial 2D screening for eligibility. Once this was confirmed and they were allocated to one of the three groups, a baseline data collection was undertaken. The exact methodology as in section

3.2.3.4 of Chapter Three, was applied in these tests. However, only one session at baseline was performed.

5.3.4.2 Follow-up data collection session.

After the participants finished the six-week intervention program, the same biomechanical measures which were collected at the baseline session were repeated in all three study groups.

5.3.5 Study intervention program.

The participants in the walking plus exercises intervention group were given a copy of training program manual similar to the feasibility study in section 4.3.5 of Chapter Four. The adherence of the participants to the study intervention program was monitored by using participant's follow-up sheet (Appendix three) which was handed to each participant at the beginning of the study. The participants were asked to follow the AposTherapy intervention guidelines for the next six weeks. The participants in just the walking intervention group followed six-week intervention program included just walking wearing the AposTherapy system for a period of 60 min during the day during normal activities. Both intervention groups performed the intervention on daily basis**.** The participants who were in the control group had no change in their normal training routine and did not use AposTherapy system.

5.4 Data processing.

All of the data were processed in the same manner as the feasibility study whereby kinematic, kinetic EMG and CoP-Excursion data processing methods previously descripted in section 3.3.4 of Chapter Three were used.

5.5 Data analysis.

An assessment of normal distribution was checked with a Shapiro-Wilk test and by visual inspection of boxplots (Ghasemi and Zahediasl, 2012). Mean ± standard deviation for all measured variables was calculated. To determine differences between the study groups the Factorial repeated measures ANOVA (3×2 Factorial ANOVA mixed between-within) for parametric data or Friedman test for non-parametric was performed to test the interaction of time and groups (walking intervention group vs walking and exercise intervention group vs control group) for each variables of interest.

Post hoc analyses were subsequently performed using the Bonferroni multiple comparison procedure to evaluate significant groups to time interactions were conducted for SLS and SLL data separately. Effect size(d) was calculated to indicated the magnitude of change in case both intervention groups showed significant changes in the dependent variable assessment. The Cohen's d values were used to calculated the effect size ($d = \frac{Xi - Xv}{\mathrm{SDc}}$) of each of the study intervention groups by using the SPSS and web site http://www.uccs.edu/faculty/backer/. A strong effect size was defined by d >0.8, moderate between 0.8 and 0.2, and low ≤0.2 (Cohen et al., 1988). Statistical significance was set at ($p<0.05$). All statistical analysis was performed in SPSS (Version 24.0. IBM SPSS Statistics, USA).

5.6 Results.

Summary of the results:

In summary, in regarding kinematic and kinetic outcomes, the main changes were observed in the walking groups, which exhibited significant reduction in knee valgus angle values during SLL task Table 5-2. Interestingly, the knee valgus angle values drop at post-test to levels exceed MDD values previously reported in reliability study in Chapter Three in section 3.2.7.2. Nevertheless, there were significant difference found between the control and the walking group. In regarding the walking and exercise group significant reduction were observed at the hip adduction moment during SLL and SLS tasks Table 5-12 and 5-16, respectively. Even though, there was significant difference observed between walking and exercise group in compared with control group during both functional tasks. Interestingly, only the hip adduction moments values during SLL drop at post-test to levels exceed MDD values previously reported in reliability study in Chapter Three in section 3.2.7.2.

In regard muscular activity no significant changes were recorded. Interestingly, the participants in the walking and exercise groups the medial knee muscular co-contraction index (VM-ST CCI) at feedforward motor control phase during SLL task showed non-significant improvement Table 5-18. Those improvements in the post-test values observed were higher than MDD values previously reported in reliability study in Chapter Three in section 3.2.7.3. Nevertheless, there was significant differences found between walking and exercise group in compare with the control group. Furthermore, the participants in the walking groups lateral knee muscular co-contraction index (VL-BF CCI) at feedback motor control phase during SLL task showed non-significant reduction in its values Table 5-21. Those changes in the post-test values observed were exceeding the MDD values previously reported in reliability study in Chapter Three in section 3.2.7.3. Furthermore, there were significant differences found between walking and the control group.

In regarding postural stability measures, both groups have demonstrated significant improvement in CoP excursion measures Table 5-27. Nevertheless, post-test values in both intervention groups were higher than MDD values previously reported in reliability study in Chapter Three in section 3.2.7.4, and a significant difference was found between control group and both intervention group. Interestingly, the effect size Table 5-27 observed in walking group were higher than effect size in the walking and exercise group.

5.6.1 Kinematic results of the supportive leg (non-dominant) during single leg landing (SLL).

5.6.1.1 Maximum knee valgus angle.

In the control group, there was no significant change (Mean difference ± SD:0.01±1.88°, p=0.92), in the maximum knee valgus angle in comparison to the baseline values. In the walking group participants, after wearing the AposTherapy system there was a significant decrease (Mean difference ± SD: 3.42±3.71°, p=0.01, d=0.51), in the maximum knee valgus angle in comparison to the baseline values. In the walking and exercise group participants, after wearing theAposTherapy system alongside the additional exercise, there was no significant change (Mean difference ± SD: 1.62±2.97°, p=0.09), in the maximum knee valgus angle in comparison to the baseline values.

There was no significant difference in knee valgus angle variables between study groups during pre-test (p>0.05). However, when observing the post-test analysis of data between three study groups there was significant difference between the control group and walking group variables (p<0.05). However, the control group and the walking and exercise group showed no significant difference regarding their post-test variables (p>0.05). Descriptive data of knee valgus angle results during SLL task are illustrated in Figure 5-1 and Table 5-2.

Table 5- 2: The mean, standard deviation (SD) and the mean difference (Mean diff.) for Knee valgus angle during SLL task.

Task	Knee Valgus Angle			
SLL	**Mean (°)**	**SD (°)**	**P**	**Effect size**
Cont gp Pre	-3.88	2.44	0.92	
Cont gp Post	-3.87	2.58		
Mean Diff	0.01	1.88		
Walk gp Pre	-4.06	3.09	0.01	0.53
Walk gp Post	-0.64	2.51		
Mean Diff	3.42	3.71		
WE gp Pre	-4.23	3.08	0.09	
WE gp Post	-2.61	2.31		
Mean Diff	1.62	2.97		

Single legged landing(SLL), control group (cont gp), Walk group (walk gp), Walking and exercise group (WE gp) and , Pre (Pre-test) and Post (Post-test).

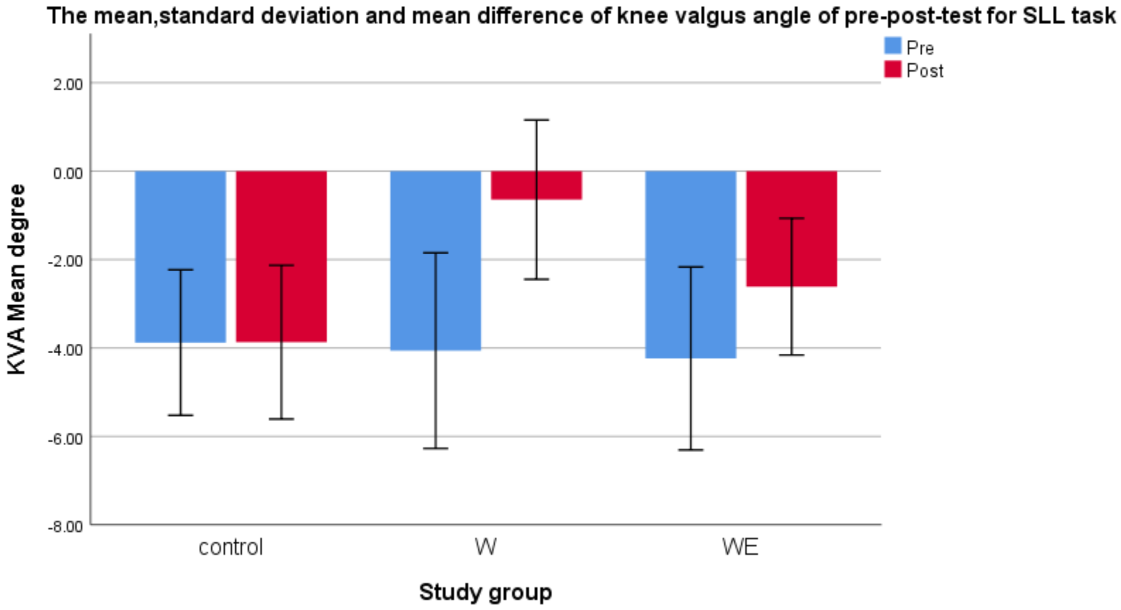


Figure 5-2: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the knee valgus angle (KVA) of pre- and post-test for SLL task. Y –axis KVA (degrees) and X-axis Sudy groups.

5.6.1.2 Maximum knee flexion angle.

In the control group, there was no significant change (Mean difference ± SD: 0.16±8.74°, p=0.86), in the maximum knee flexion angle in comparison to the baseline values. In the walking participants group, after wearing the AposTherapy system, there was no significant change (Mean difference ± SD: 0.28±8.29°, p=0.91), in the maximum knee flexion angle in comparison to the baseline values. In the walking and exercise group participants, after wearing the AposTherapy system alongside the additional exercise, there was no significant change (Mean difference ± SD: 5.79±15.01°, p=0.23), in the maximum knee flexion angle in comparison to the baseline values.

There was no significant difference in knee flexion angle variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of knee flexion angle results during SLL task are illustrated in Table 5-3.

Table 5- 3: The mean, standard deviation (SD) and the mean difference (Mean diff.) for Knee flexion angle during SLL task.

Task	Knee Flexion Angle		
SLL	Mean (°)	SD (°)	P
Cont gp Pre	72.69	9.49	0.95
Cont gp Post	72.52	9.73	
Mean Diff	0.16	8.74	
Walk gp Pre	64.75	7.45	0.91
Walk gp Post	65.03	10.89	
Mean Diff	0.28	8.29	
WE gp Pre	69.75	7.25	0.23
WE gp Post	63.96	12.44	
Mean Diff	5.79	15.01	

Single legged landing (SLL), control group (cont gp), Walk group (walk gp), Walking and exercise group (WE gp), Pre (Pre-test), and Post (Post-test).

5.6.1.3 Maximum hip adduction angle.

In the control group, there was no significant change (Mean difference ± SD: 1.34±3.11°, p=0.18), in the maximum hip adduction angle in comparison to the baseline values. In the walking group after wearing the AposTherapy system, there was no significant change (Mean difference ± SD: 1.23±4.64°, p=0.42), in the maximum hip adduction angle in comparison to the baseline values. In the walking and exercise group after wearing the AposTherapy system alongside the additional exercise, there was no significant changes (Mean difference ± SD:

4.31±7.04°, p=0.07), in the maximum hip adduction angle in comparison to the baseline values.

There was no significant difference in hip adduction angle variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of hip adduction angle results during SLL task are illustrated in Table 5-4.

Table 5- 4: The mean, standard deviation (SD) and the mean difference (Mean diff.) for Hip adduction angle during SLL task.

Task	**Hip Adduction Angle**		
SLL	Mean (°)	SD (°)	P
Cont gp Pre	2.36	2.56	0.18
Cont gp Post	3.71	3.35	
Mean Diff	1.34	3.11	
Walk gp Pre	4.93	5.52	0.42
Walk gp Post	3.69	5.22	
Mean Diff	1.23	4.64	
WE gp Pre	7.13	5.49	0.07
WE gp Post	2.82	6.96	
Mean Diff	4.31	7.04	

Single legged landing (SLL), control group (cont gp), Walk group (walk gp), Walking and exercise group (WE gp) , Pre (Pre-test), and Post (Post-test).

5.6.1.4 Maximum ankle dorsiflexion Angle.

In the control group, there was no significant change (Mean difference ± SD: 2.29±4.31°, p=0.11), in the maximum dorsiflexion angle in comparison to the baseline values. In the walking group after wearing the AposTherapy system, there was no significant change (Mean difference ±SD: 0.47±4.97°, p=0.7), in the maximum dorsiflexion angle in comparison to the baseline values. In the walking and exercise group after wearing the AposTherapy system alongside the additional exercise, there no significant changes (Mean difference ±SD :3.40 ±7.32°, p=0.15), in the maximum dorsiflexion angle in comparison to the baseline values.

There was no significant difference in dorsiflexion angle variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of dorsiflexion angle results during SLL task are illustrated in Table 5-5.

Table 5- 5: The mean, standard deviation (SD) and the mean difference (Mean diff.) for dorsiflexion angle during SLL task.

Task	**Ankle Dorsiflexion Angle**		
SLL	Mean (°)	SD (°)	P
Cont gp Pre	30.60	3.38	0.10
Cont gp Post	28.30	5.00	
Mean Diff	2.29	4.31	
Walk gp Pre	28.03	3.38	0.77
Walk gp Post	27.56	4.47	
Mean Diff	0.47	4.97	
WE gp Pre	29.58	4.34	0.15
WE gp Post	26.18	6.80	
Mean Diff	3.40	7.32	

Single legged landing (SLL), control group (cont gp), Walk group (walk gp), Walking and exercise group (WE gp), Pre (Pre-test), and Post (Post-test).

5.6.2 Kinematic results of the supportive leg (non-dominant) during single leg squat (SLS).

5.6.2.1 Maximum knee valgus angle.

In the control group, there was no significant change (Mean difference ± SD: 1.51±0.59°, p=0.08) in the maximum knee valgus angle in comparison to the baseline values. In the walking group after wearing the AposTherapy system, there was no significant change (Mean difference ± SD: 1.13±2.7°, p=0.22) in the maximum knee valgus angle in comparison to the baseline values. In the walking and exercise group after wearing the AposTherapy system alongside the additional exercise, there was no significant change (Mean difference ± SD: 0.49±1.82°, p=0.91), in the maximum knee valgus angle in comparison to the baseline values.

There was no significant difference in knee valgus angle between any two of the three study groups in pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of knee valgus angle results during SLS task are illustrated in Table 5-6.

Table 5- 6: The mean, standard deviation (SD) and the mean difference (Mean diff.) for Knee valgus angle during SLS task.

Task	Knee Valgus Angle		
SLS	Mean (°)	SD (°)	P
Cont gp Pre	-2.43	2.4	0.08
Cont gp Post	-3.94	2.77	
Mean Diff	1.51	0.59	
Walk gp Pre	-4.22	3.45	0.22
Walk gp Post	-3.09	1.57	
Mean Diff	1.13	2.78	
WE gp Pre	-3.96	2.69	0.91
WE gp Post	-3.47	2.63	
Mean Diff	0.49	1.82	

Single leg squat (SLS), control group (cont gp), Walk group (walk gp), Walking and exercise group(WE gp), Pre (Pre-test),and Post (Post-test).

5.6.2.2 Maximum knee flexion angle.

In the control group, there was no significant change (Mean difference ± SD: 0.53±4.29°, p=0.08), in the maximum knee flexion angle in comparison to the baseline values. In the walking group after wearing the AposTherapy system there was no significant change (Mean difference ±SD: 0.62±10.15°, p=0.85), in the maximum knee flexion angle in comparison to the baseline values. In the walking and exercise group after wearing the AposTherapy system alongside the additional exercise, there was no significant change (Mean difference ±SD: 1.20±4.26°, p=0.36), in the maximum knee flexion angle in comparison to the baseline values.

There was no significant difference in knee flexion angle variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of knee flexion angle results during SLS task are illustrated in Table 5-7.

Table 5- 7: The mean, standard deviation (SD) and the mean difference (Mean diff.) for Knee flexion angle during SLS task.

Task	Knee Flexion Angle		
SLS	Mean (°)	SD (°)	P
Cont gp Pre	79.58	9.22	0.68
Cont gp Post	79.04	9.29	
Mean Diff	0.53	4.29	
Walk gp Pre	73.43	7.43	0.85
Walk gp Post	74.08	13.67	
Mean Diff	0.62	10.15	
WE gp Pre	76.82	4.84	0.36
WE gp Post	75.61	5.48	
Mean Diff	1.21	4.26	

Single leg squat (SLS), control group (cont gp) , Walk group(walk gp),Walking and exercise group(WE gp) , Pre (Pre-test), and Post (Post-test).

5.6.2.3 Maximum hip adduction angle.

In the control group, there was no significant change (Mean difference ± SD: 1.44±3.25°, p=0.17), in the maximum hip adduction angle in comparison to the baseline values. In the walking group after wearing the AposTherapy system for the study intervention period for 6 weeks, there was no significant change (Mean difference ±SD 3.49±8.56°, p=0.23), in the maximum hip adduction angle in comparison to the baseline values. In the walking and exercise group after wearing the AposTherapy system alongside the additional exercise, there was no significant change (Mean difference ±SD 2.15±4.06°, p=0.1), in the maximum hip adduction angle in comparison to the baseline values.

There was no significant difference in hip adduction angle variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of hip adduction angle results during SLS task are illustrated in Table 5-8.

Table 5- 8: The mean, standard deviation (SD) and the mean difference (Mean diff.) for Hip adduction angle during SLS task.

Task	**Hip Adduction Angle**		
SLS	Mean (°)	SD (°)	P
Cont gp Pre	11.52	5.55	0.17
Cont gp Post	12.96	6.08	
Mean Diff	1.44	3.25	
Walk gp Pre	9.26	5.16	0.23
Walk gp Post	12.75	6.91	
Mean Diff	3.49	8.56	
WE gp Pre	15.45	6.08	0.10
WE gp Post	13.29	5.91	
Mean Diff	2.15	4.06	

Single leg squat (SLS), control group (cont gp), Walk group(walk gp),Walking and exercise group(WE gp) , Pre (Pre-test), and Post (Post-test).

5.6.2.4 Maximum ankle dorsiflexion angle.

In the control group, there was no significant change (Mean difference ± SD: 0.83±1.48°, p=0.09), in the maximum dorsiflexion angle in comparison to the baseline values. In the walking group after wearing the AposTherapy system, there was no significant change (Mean difference ±SD: 0.37±4.02°, p=0.7), in the maximum dorsiflexion angle in comparison to the baseline values. In the walking and exercise group after wearing the AposTherapy system alongside the additional exercise, there was no significant changes (Mean difference ±SD: 0.38 ±2.73°, p=0.53), in the maximum dorsiflexion angle in comparison to the baseline values.

There was no significant difference in dorsiflexion angle variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of Dorsiflexion angle results during SLS task are illustrated in Table 5-9.

Table 5- 9: The mean, standard deviation (SD) and the mean difference (Mean diff.) for Dorsiflexion angle during SLS task.

Task	Dorsiflexion Angle		
SLS	Mean (°)	SD (°)	P
Cont gp Pre	34.56	4.88	0.09
Cont gp Post	33.73	5.50	
Mean Diff	0.83	1.48	
Walk gp Pre	33.19	3.18	0.77
Walk gp Post	32.81	4.46	
Mean Diff	0.37	4.02	
WE gp Pre	34.16	2.71	0.53
WE gp Post	33.77	2.68	
Mean Diff	0.38	2.73	

Single leg squat (SLS), control group (cont gp), Walk group(walk gp),Walking and exercise group(WE gp) , Pre (Pre-test), and Post (Post-test).

5.6.3 Kinetic results of the supportive leg (non-dominant) during single leg landing (SLL).

5.6.3.1 Maximum external knee valgus moment.

In the control group, there was no significant change (Mean difference ± SD: 0.01±0.046 Nm/kg, p=0.4), in the maximum knee valgus moment in comparison to the baseline values. In the walking group after wearing the AposTherapy system, there was no significant change (Mean difference±SD:0.056±0.083 Nm/kg, p=0.05), in the maximum knee valgus moment in comparison to the baseline values. In the walking and exercise group after wearing the AposTherapy system alongside the additional exercise, there was no significant change (Mean difference ±SD:0.013±0.17 Nm/kg, p=0.8), in the maximum knee valgus moment in comparison to the baseline values.

There was no significant difference in knee valgus moment variables between study groups during pre-test (p>0.05). However, when observing the post-test analysis of data between three study groups there was significant difference between the control group and walking group variables (p<0.05). Furthermore, the control group and the walking and exercise group showed no significant difference regarding their post-test variables (p>0.05). Descriptive data of knee valgus moment results during SLL task are illustrated in Table 5-10.

Table 5- 10: The mean, standard deviation (SD) and the mean difference (Mean diff.) for Knee valgus moment during SLL task.

Task	Knee Valgus Moment		
SLL	Mean(Nm/kg)	SD(Nm/kg)	P
Cont gp Pre	0.146	0.15	0.46
Cont gp Post	0.139	0.79	
Mean Diff	0.007	0.046	
Walk gp Pre	0.154	0.076	0.05
Walk gp Post	0.097	0.13	
Mean Diff	0.056	0.083	
WE gp Pre	0.172	0.157	0.8
WE gp Post	0.186	0.127	
Mean Diff	0.013	0.17	

Single legged landing (SLL), control group (cont gp), Walk group (walk gp), Walking and exercise group (WE gp), Pre (Pre-test), and Post (Post-test).

5.6.3.2 Maximum external knee flexion Moment.

In the control group, there was no significant change (Mean difference ± SD: 0.01±0.18 Nm/kg, p=0.86), in the maximum knee flexion moment in comparison to the baseline values. In the walking group after wearing the AposTherapy system, there was no significant change (Mean difference ±SD: 0.20±1.33 Nm/kg, p=0.87), in the maximum knee flexion moment in comparison to the baseline values. In the walking and exercise group after wearing the AposTherapy system alongside the additional exercise, there was no significant change (Mean difference ±SD: 0.014±0.27 Nm/kg, p=0.8), in the maximum knee flexion moment in comparison to the baseline values.

There was no significant difference in knee flexion moment variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of knee flexion moment results during SLL task are illustrated in Table 5-11.

Table 5- 11: The mean, standard deviation (SD) and the mean difference (Mean diff.) for Knee flexion moment during SLL task.

Task	**Knee Flexion Moment**		
SLL	Mean(Nm/kg)	SD(Nm/kg)	P
Cont gp Pre	2.1	0.32	0.86
Cont gp Post	2.11	0.31	
Mean Diff	0.01	0.18	
Walk gp Pre	1.73	0.89	0.87
Walk gp Post	1.93	0.66	
Mean Diff	0.2	1.33	
WE gp Pre	2.06	0.26	0.92
WE gp Post	2.08	0.29	
Mean Diff	0.014	0.27	

Single legged landing (SLL), control group (cont gp), Walk group (walk gp), Walking and exercise group(WE gp) , Pre (Pre-test), and Post (Post-test).

5.6.3.3 Maximum external hip adduction moment.

In the control group, there was no significant change (Mean difference ± SD: 0.44±1.44 Nm/kg, p=0.53), in the maximum hip adduction moment in comparison to the baseline values. In the walking group after wearing the AposTherapy system, there was no significant change (Mean difference ±SD: 0.11±0.76 Nm/kg, p=0.64), in the maximum hip adduction moment in comparison to the baseline values. In the walking and exercise group after wearing the AposTherapy system, alongside the additional exercise, there was significant decrease (Mean difference ±SD: 0.38±0.49 Nm/kg, p=0.02, d=2.28), in the maximum hip adduction moment in comparison to the baseline values.

There was no significant difference in hip adduction moment variables between study groups during pre-test (p>0.05). However, when observing the post-test analysis of data between three study groups there was significant difference between the control group and walking and exercise group variables (p<0.05). Furthermore, the control group and the walking group showed no significant difference regarding their post-test variables (p>0.05). Descriptive data of hip adduction moment results during SLL task are illustrated in Figure 5-2 and Table 5-12.

Table 5- 12: The mean, standard deviation (SD) and the mean difference (Mean diff.) for Hip adduction moment during SLL task.

Task	Hip Adduction Moment			
SLL	Mean(Nm/kg)	SD(Nm/kg)	P	Effect size
Cont gp Pre	1.6	1.36	0.53	
Cont gp Post	1.15	0.32		
Mean Diff	0.44	1.44		
Walk gp Pre	1.39	0.57	0.64	
Walk gp Post	1.49	0.5		
Mean Diff	0.11	0.76		
WE gp Pre	1.46	0.41	0.02	2.28
WE gp Post	1.07	0.19		
Mean Diff	0.38	0.49		

Single legged landing (SLL), control group (cont gp), Walk group (walk gp), Walking and exercise group(WE gp) , Pre (Pre-test), and Post (Post-test).

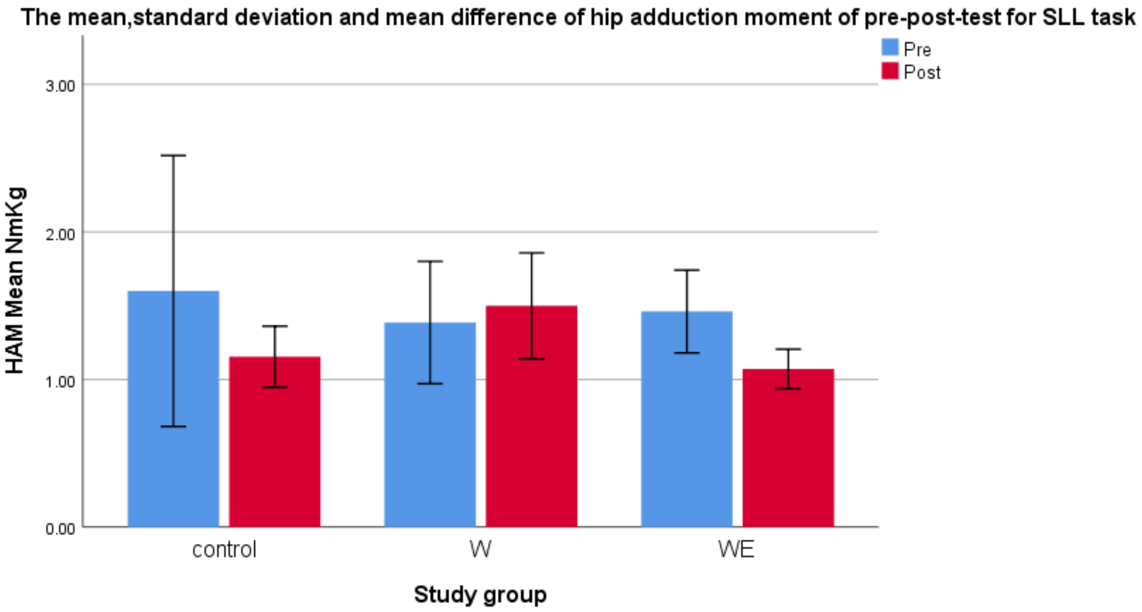


Figure 5-3: The mean, standard deciation (SD) and the mean difference (Mean diff) of the Hip adduction moment (HAM) of pre-and post-test for SLL task. Y –axis HAM (Nm/kg) and X-axis Sudy groups.

5.6.3.4 Maximum vertical ground reaction force (GRF).

In the control group, there was no significant change (Mean difference ±SD: 0.10±0.32 ∗BW p=0.31), in the maximum vertical ground reaction force in comparison to their baseline values. In the walking group after wearing the AposTherapy system, there was no significant change (Mean difference ±SD: 0.024±0.33 ∗BW, p=0.72), in the maximum vertical ground reaction force in comparison to their baseline values. In the walking and exercise group after wearing the AposTherapy system alongside the additional exercise, there was no significant change (Mean difference ±SD: 0.039±0.29∗BW, p=0.65), in the maximum vertical ground reaction force in comparison to their baseline values.

There was no significant difference in the GRF variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of Vertical Ground Reaction Force results during SLL task are illustrated in Table 5-13.

Table 5- 13: The mean, standard deviation (SD) and the mean difference (Mean diff.) for GRF during SLL task.

Task	GRF		
SLL	Mean(∗BW)	SD(∗BW)	P
Cont gp Pre	2.37	0.33	0.31
Cont gp Post	2.26	0.24	
Mean Diff	0.1	0.32	
Walk gp Pre	2.30	0.41	0.72
Walk gp Post	2.24	0.44	
Mean Diff	0.06	0.33	
WE gp Pre	2.56	0.39	0.65
WE gp post	2.58	0.34	
Mean diff	0.02	0.29	

Single legged landing (SLL), Ground reaction force (GRF), control group (cont gp) , Walk group(walk gp),Walking and exercise group(WE gp), Pre (Pre-test), and Post (Post-test).

5.6.4 Kinetic results of the supportive leg (non-dominant) during single leg squat (SLS).

5.6.4.1 Maximum external knee valgus moment.

In the control group, there was no significant change (Mean difference ± SD: 0.0073±0.032 Nm/kg, p=0.46), in the maximum knee valgus moment in comparison to the baseline values. In the walking group after wearing the AposTherapy system there was no significant change (Mean difference ±SD: 0.012±0.029 Nm/kg, p=0.20), in the maximum knee valgus moment in comparison to the baseline values. In the walking and exercise group after wearing the AposTherapy system alongside the additional exercise, there was no significant change

(Mean difference ±SD: 0.003±0.035 Nm/kg, p=0.8), in the maximum knee valgus moment in comparison to the baseline values.

There was no significant difference in knee valgus moment variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of knee valgus moment results during SLS task are illustrated in Table 5-14.

Table 5- 14: The mean, standard deviation (SD) and the mean difference (Mean diff.) for Knee valgus moment during SLS task.

Task	**Knee Valgus Moment**		
SLS	Mean(Nm/kg)	SD(Nm/kg)	P
Cont gp Pre	0.051	0.034	0.46
Cont gp Post	0.058	0.027	
Mean Diff	0.007	0.032	
Walk gp Pre	0.056	0.043	0.2
Walk gp Post	0.043	0.025	
Mean Diff	0.012	0.029	
WE gp Pre	0.073	0.049	0.8
WE gp Post	0.076	0.59	
Mean Diff	0.003	0.03	

Single leg squat (SLS), control group (cont gp), Walk group (walk gp), Walking and exercise group (WE gp), Pre (Pre-test), and Post (Post-test).

5.6.4.2 Maximum external knee flexion moment.

In the control group, there was no significant change (Mean difference ± SD: 0.002±0.20Nm/kg, p=0.86), in the maximum knee flexion moment in comparison to the baseline values. In the walking group after wearing the AposTherapy system, there was no significant change (Mean difference ±SD: 0.031±0.31 Nm/kg, p=0.76), in the maximum knee flexion moment in comparison to the baseline values. In the walking and exercise group after wearing the AposTherapy system alongside the additional exercise, there was no significant change (Mean difference ±SD: 0.069±0.24 Nm/kg, p=0.37), in the maximum knee flexion moment in comparison to the baseline values.

There was no significant difference in knee flexion moment variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of knee flexion moment results during SLS task are illustrated in Table 5-15.

Table 5- 15: The mean, standard deviation (SD) and the mean difference (Mean diff.) for Knee flexion moment during SLS task.

Task	**Knee Flexion Moment**		
SLS	Mean(Nm/kg)	SD(Nm/kg)	P
Cont gp Pre	1.58	0.31	0.86
Cont gp Post	1.58	0.29	
Mean Diff	0.002	0.2	
Walk gp Pre	1.54	0.27	0.76
Walk gp Post	1.57	0.29	
Mean Diff	0.031	0.31	
WE gp Pre	1.61	0.24	0.37
WE gp Post	1.54	0.16	
Mean Diff	0.069	0.24	

Single leg squat (SLS), control group (cont gp), Walk group (walk gp), Walking and exercise group (WE gp) , Pre (Pre-test), and Post (Post-test).

5.6.4.3 Maximum hip adduction moment.

In the control group, there was no significant change (Mean difference ± SD: 0.25±0.39 Nm/kg, p=0.86), in the maximum hip adduction moment in comparison to the baseline values. In the walking group after wearing the AposTherapy system, there was no significant change (Mean difference ±SD: 0.17±0.59 Nm/kg, p=0.15), in the maximum hip adduction moment in comparison to the baseline values. In the walking and exercise group after wearing the AposTherapy system alongside the additional exercise, there was significant decrease (Mean difference ±SD: 0.22±0.59 Nm/kg, p=0.03, d=0.41), in the maximum hip adduction moment in comparison to the baseline values.

There was no significant difference in hip adduction moment variables between study groups during pre-test (p>0.05). However, when observing the post-test analysis of data between three study groups there was no significant difference between the control group and walking group variables(p>0.05). However, the control group and the walking and exercise group showed significant difference regarding their post-test variables ($p<0.05$). Descriptive data of hip adduction moment results during SLS task are illustrated in Figure 5-3 and Table 5-16.

Table 5- 16: The mean, standard deviation (SD) and the mean difference (Mean diff.) for Hip adduction moment during SLS task.

Task	**Hip Adduction Moment**			
SLS	Mean(Nm/kg)	SD(Nm/kg)	P	Effect size
Cont gp Pre	0.88	0.13	0.86	
Cont gp Post	1.13	0.43		
Mean Diff	0.25	0.39		
Walk Pre	1.01	0.29	0.15	
Walk Post	1.19	0.52		
Mean Diff	0.17	0.59		
WE Pre	1.30	0.61	0.03	0.41
WE Post	1.08	0.45		
Mean Diff	0.22	0.59		

Single leg squat (SLS), control group (cont gp), Walk group (walk gp), Walking and exercise group (WE gp), Pre (Pre-test), and Post (Post-test).

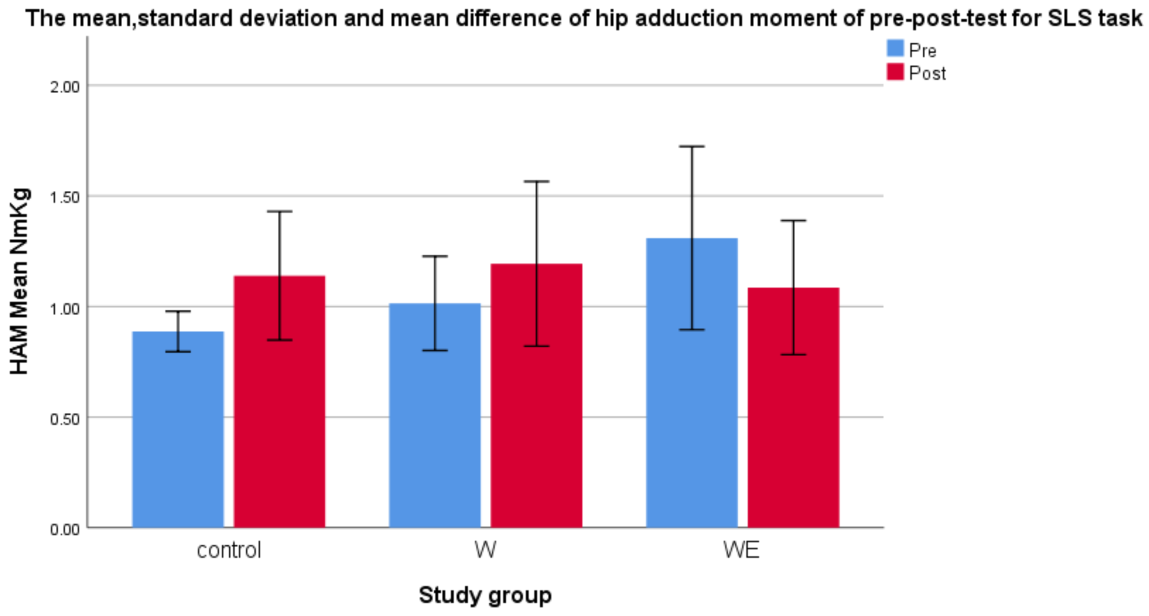


Figure 5-4: The mean, standard deciation (SD) and the mean difference (Mean diff) of the Hip adduction moment (HAM) of pre-and post-test for SLS task. Y –axis HAM (Nm/kg) and X-axis Sudy groups.

5.6.4.4 Maximum vertical ground reaction force (GRF).

In the control group, there was no significant change (Mean difference ±SD: 0.10±0.32 ∗BW p=0.42), in the maximum vertical ground reaction force in comparison to their baseline values. In the walking group after wearing the AposTherapy system, there was no significant change (Mean difference ±SD: 0.02±0.04 ∗BW, p=0.18), in the maximum vertical ground reaction force in comparison to their baseline values. In the walking and exercise group participants after wearing the AposTherapy system alongside the additional exercise, there was no significant change (Mean difference ±SD: 0.005±0.06 ∗BW, p=0.76), in the maximum vertical ground reaction force in comparison to their baseline values.

There was no significant difference in GRF variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of GRF results during SLS task are illustrated in Table 5-17.

Table 5- 17: The mean, standard deviation (SD) and the mean difference (Mean diff.) for GRF during SLS task.

Task	**GRF**		
SLS	Mean(∗BW)	SD(∗BW)	P
Cont gp Pre	1.11	0.03	0.42
Cont gp Post	1.12	0.06	
Mean Diff	0.01	0.057	
Walk gp Pre	1.13	0.09	0.18
Walk gp Post	1.10	0.07	
Mean diff	0.03	0.04	
WE gp Pre	1.13	0.08	0.78
WE gp Post	1.14	0.11	
Mean diff	0.005	0.06	

Single leg squat (SLL), Ground reaction forces (GRF), control group (cont gp) , Walk group(walk gp),Walking and exercise group(WE gp) , Pre (Pre-test), and Post (Post-test).

5.6.5 Electromyography results of the supportive leg (non-dominant) during single leg landing (SLL).

When looking between the pre-post assessments for the three study groups, there were no significant difference in any of the measures.

5.6.5.1 Medial side knee muscle Vastus Medialis and Semitendinosus (VM-ST) co-contraction index during feed-forward motor control phase (100ms prior to initial contact) during SLL task.

There was no significant difference in the maximum Vastus Medialis and Semitendinosus (VM-ST) co-contraction index at feed-forward motor control phase during SLL task variables between study groups during pre-test (p>0.05). While observing the post-test analysis of data between three study groups there was no significant difference between the control group and walking group variables(p>0.05). However, the control group and the walking and exercise group showed significant difference regarding their post-test variables (p<0.05). Descriptive data of results Vastus Medialis and Semitendinosus (VM-ST) co-contraction index at feed-forward motor control phase (100 ms prior to initial contact), during SLL task are illustrated in Figure 5-4 and Table 5-18.

Table 5- 18: The mean, standard deviation (SD) and the mean difference (Mean diff.) of % MVIC, for (VM-ST) co-contraction index at feed-forward motor control phase during SLL task.

Task	**VM-ST CCI Feed-forward**		
SLL	Mean(%MVIC)	SD(%MVIC)	P
Cont gp Pre	37.63	13.18	0.12
Cont gp Post	29.81	10.09	
Mean Diff	7.81	15.54	
Walk gp Pre	48.5	15.56	0.9
Walk gp Post	42.7	26.72	
Mean Diff	5.8	30.94	
WE gp Pre	48.45	21.94	0.09
WE gp Post	60.27	32.67	
Mean Diff	11.81	44.29	

Single legged landing (SLL), Vastus Medialis and Semitendinosus (VM-ST) , control group (cont gp) , Walk group(walk gp),Walking and exercise group(WE gp), Pre (Pre-test),Post (Post-test) and Co-contraction index (CCI).

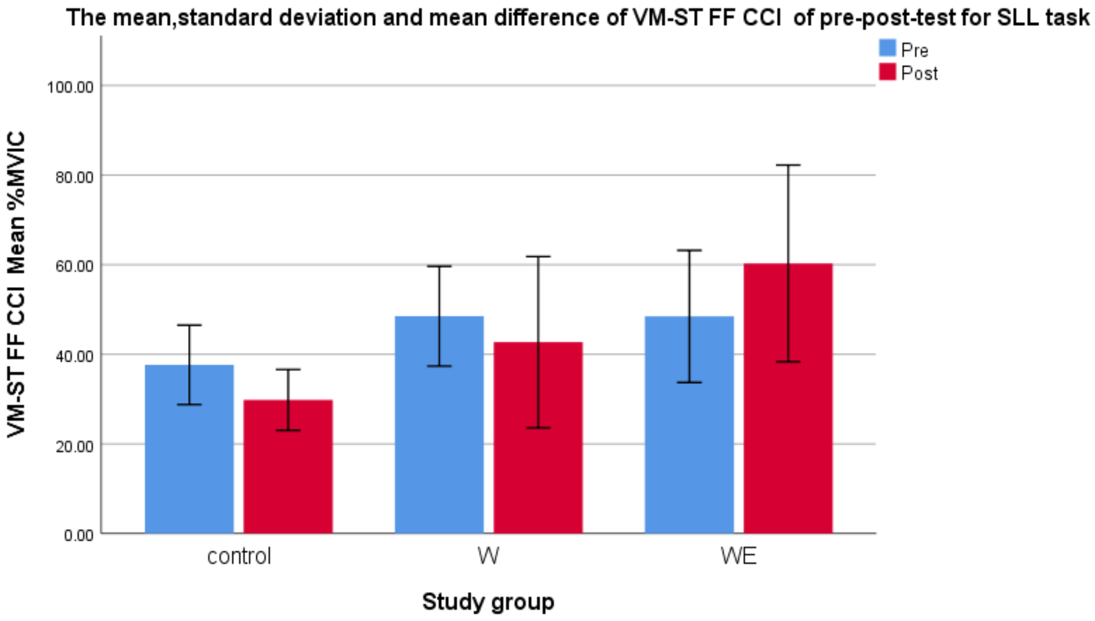


Figure 5-5: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the (VM-ST) co-contraction index at feed forward motor control phase of pre- and post-test for SLL task. Y –axis VM-ST CCI Feed-forward (%MVIC) and X-axis Sudy groups.

5.6.5.2 Medial side knee muscle Vastus Medialis and Semitendinosus (VM-ST) co-contraction index during feed-back motor control phase (100ms prior to initial contact) during SLL task.

There was no significant difference in the maximum Vastus Medialis and Semitendinosus (VM-ST) co-contraction index at feed-back motor control phase during SLL task variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of results Vastus Medialis and Semitendinosus (VM-ST) co-contraction index at feed-back motor control phase (100ms after to initial contact), during SLL task are illustrated in Table 5-19.

Table 5- 19: The mean, standard deviation (SD) and the mean difference (Mean diff.) of % MVIC, for (VM-ST) co-contraction index at feed-back motor control phase during SLL task.

Task	VM-ST CCI Feed-back		
SLL	**Mean(%MVIC)**	**SD(%MVIC)**	**P**
Cont gp Pre	45.18	20.52	0.17
Cont gp Post	36.01	19.32	
Mean Diff	9.18	20.77	

Walk gp Pre	44.1	16.6	0.7
Walk gp Post	58.1	53.51	
Mean Diff	14	44.01	
WE gp Pre	60.63	22.02	0.9
WE gp Post	62.81	34.6	
Mean Diff	2.18	35.9	

Single legged landing (SLL), Vastus Medialis and Semitendinosus (VM-ST), control group (cont gp), Walk group (walk gp), Walking and exercise group (WE gp), Pre (Pre-test),Post (Post-test) and Co-contraction index (CCI).

5.6.5.3 Lateral side knee muscle Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index during feed-forward motor control phase (100 ms prior to initial contact) during SLL task.

There was no significant difference in the maximum Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index at feed-forward motor control phase during SLL task variables between study groups during pre-test ($p>0.05$), nor during the post-test variables between the study groups ($p>0.05$). Descriptive data of results Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index at feed-forward motor control phase (100 ms prior to initial contact), during SLL task are illustrated in Table 5-20.

Table 5- 20: The mean, standard deviation (SD) and the mean difference (Mean diff.) of % MVIC, for (VL-BF) co-contraction index at feed-forward motor control phase during SLL task.

Task SLS	**VL-BF CCI Feed-forward**		
SLL	Mean(%MVIC)	SD(%MVIC)	P
Cont gp Pre	49.45	16.39	0.12
Cont gp Post	41.18	17.88	
Mean Diff	8.27	16.16	
Walk gp Pre	61.1	33.04	0.8
Walk gp Post	58.9	28.61	
Mean Diff	2.2	44.72	
WE gp Pre	57.63	23.28	0.29
WE gp Post	69.63	38.39	
Mean Diff	12	36	

Single legged landing (SLL), Vastus Lateralis and Biceps Femoris (VL-BF), control group (cont gp) , Walk group(walk gp),Walking and exercise group(WE gp) , Pre (Pre-test),Post (Post-test) and Co-contraction index (CCI).

5.6.5.4 Lateral side knee muscle Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index during feed-back motor control phase (100 ms after to initial contact) during SLL task.

There was no significant difference in the maximum Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index at feed-back motor control phase during SLL task variables between study groups during pre-test (p>0.05), While observing the post-test analysis of data between three study groups there was no significant difference between the control group and walking and exercise group variables(p>0.05). However, the control group and the walking group showed significant difference regarding their post-test variables (p<0.05). Descriptive data of results Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index at feed-back motor control phase (100ms prior to initial contact), during SLL task are illustrated in Figure 5-5 and Table 5-21.

Table 5- 21: The mean, standard deviation (SD) and the mean difference (Mean diff.) of % MVIC for (VL-BF) co-contraction index at feed-back motor control phase during SLL task.

Task	VL-BF CCI Feed-back		
SLL	Mean(%MVIC)	SD(%MVIC)	P
Cont gp Pre	41.63	13.61	0.62
Cont gp Post	44.09	22.7	
Mean Diff	2.45	16.16	
Walk gp Pre	69.01	42.1	0.07
Walk gp Post	42.7	18.7	
Mean Diff	26.3	47.88	
WE gp Pre	69.36	40.74	0.91
WE gp Post	65.63	32.9	
Mean Diff	3.72	29.85	

Single legged landing (SLL), Vastus Lateralis and Biceps Femoris (VL-BF), control group (cont gp) , Walk group(walk gp),Walking and exercise group(WE gp) , Pre (Pre-test),Post (Post-test) and Co-contraction index (CCI).

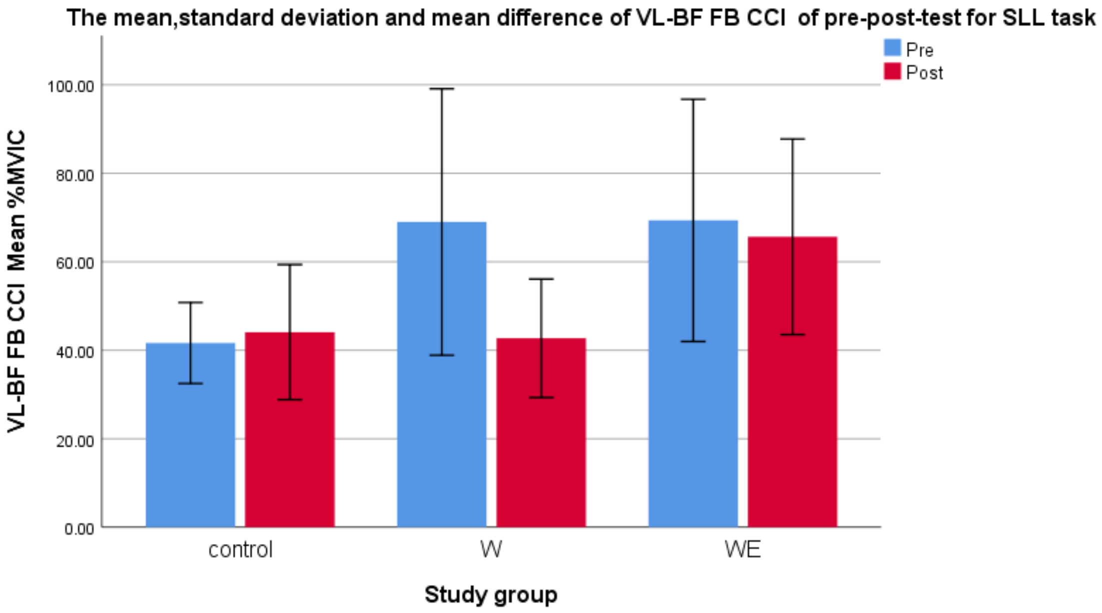


Figure 5-6: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the (VL-BF) co-contraction index at fee-dback motor control phase of pre- post-test for SLL task. Y –axis VL-BF CCI Feed-back (%MVIC) and X-axis Sudy groups

5.6.5.5 Medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-forward phase motor control phase (100ms prior to initial contact) during SLL task.

There was no significant difference in the medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-forward motor control phase during SLL variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of results in the medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-forward motor control phase (100ms prior to initial contact) during SLL task are illustrated in Table 5-22.

Table 5- 22: The mean, standard deviation (SD) and the mean difference (Mean diff.) of % MVIC, for the medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-forward motor control phase during SLL task.

Task	**Medial (VM-ST) /Lateral (VL-BF) CCI ration Feed-forward**		
SLL	Mean	SD	P
Cont gp Pre	0.95	0.35	0.16
Cont gp Post	1.01	0.41	
Mean Diff	0.06	0.39	
Walk gp Pre	1.03	0.56	0.58

Walk gp Post	1.15	1.02	
Mean Diff	0.12	0.66	
WE gp Pre	0.98	0.51	0.58
WE gp Post	1.19	0.54	
Mean Diff	0.21	0.67	

Single legged landing (SLL), the medial knee muscles the Vastus Medialis and Semitendinosus (VM-ST) to lateral knee muscles the Vastus Lateralis and Biceps Femoris (VL-BF), control group (cont gp) , Walk group(walk gp),Walking and exercise group(WE gp), Pre (Pre-test),Post (Post-test) and Co-contraction index (CCI).

5.6.5.6 Medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-back motor control phase (100ms after to initial contact) during SLL task.

There was no significant difference in the medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-back motor control phase during SLL variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of results in the medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-back motor control phase (100ms after to initial contact) during SLL task are illustrated in Table 5-23.

Table 5- 23: Mean ±SD and p value The mean, standard deviation (SD) and the mean difference (Mean diff.) for the medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-back motor control phase during SLL task.

Task	**Medial (VM-ST) / Lateral (VL-BF) CCI ration Feed-back**		
SLL	Mean	SD	P
Cont gp Pre	0.89	0.52	0.59
Cont gp Post	0.93	0.74	
Mean Diff	0.04	0.61	
Walk gp Pre	0.74	0.27	0.11
Walk gp Post	0.96	0.41	
Mean Diff	0.22	0.39	
WE gp Pre	1.41	1.40	0.56
WE gp Post	1.23	0.97	
Mean Diff	0.17	0.71	

Single legged landing (SLL), the medial knee muscles the Vastus Medialis and Semitendinosus (VM-ST) to lateral knee muscles the Vastus Lateralis and Biceps Femoris (VL-BF), control group (cont gp) , Walk group(walk gp),Walking and exercise group(WE gp), Pre (Pre-test),Post (Post-test) and Co-contraction index (CCI).

5.6.6 Electromyography results of the of the supportive leg (non-dominant) during single leg squat task (SLS).

5.6.6.1 Medial side knee muscle Vastus Medialis and Semitendinosus (VM-ST) co-contraction index during SLS task.

There was no significant difference in the maximum Vastus Medial and Semitendinosus (VM-ST) co-contraction index during SLS task variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of results Vastus Medialis and Semitendinosus (VM-ST) co-contraction index during SLS task are illustrated in Table 5-24.

Table 5- 24: The mean, standard deviation (SD) and the mean difference (Mean diff.) of % MVIC for the medial (VM-ST) co-contraction index during SLS task.

Task	**VM-ST CCI**		
SLS	Mean(%MVIC)	SD(%MVIC)	P
Control Pre	42.54	20.34	0.12
Control Post	32.95	12.83	
Mean Diff	9.63	19.22	
Walk Pre	54.2	14.83	0.21
Walk Post	44.5	23.81	
Mean Diff	9.71	23.08	
WE Pre	58.36	39.8	0.42
WE Post	69.45	58.92	
Mean Diff	11.09	31.41	

Single leg squat (SLS), Vastus Medialis and Semitendinosus (VM-ST), control group (cont gp) , Walk group(walk gp),Walking and exercise group(WE gp), Pre (Pre-test),Post (Post-test) and Co-contraction index (CCI).

5.6.6.2 Lateral side knee muscle Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index) during SLS task.

There was no significant difference in the maximum Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index during SLS variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of results Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index during SLS task are illustrated in Table 5-25.

Table 5- 25: The mean, standard deviation (SD) and the mean difference (Mean diff.) of %MVIC for lateral (VL-BF) co-contraction index during SLS task.

Task	**VL-BF CCI**		
SLS	Mean(%MVIC)	SD(%MVIC)	P
Cont gp Pre	47.81	21.63	0.8
Cont gp Post	48.81	21.53	
Mean Diff	1.01	15.24	
Walk gp Pre	49.56	21.38	0.8
Walk gp Post	46.61	24.84	
Mean Diff	2.95	38.15	
WE gp Pre	67.81	45.89	0.14
WE gp Post	56.72	31.58	
Mean Diff	11.19	23.21	

Single leg squat (SLS), Vastus Lateralis and Biceps Femoris (VL-BF), control group (cont gp), Walk group (walk gp), Walking and exercise group (WE gp) Pre (Pre-test) and Post (Post-test) and Co-contraction index (CCI).

5.6.6.3 Medial (VM-ST) to lateral (VL-BF) co-contraction index ration during SLS task.

There was no significant difference in the medial (VM-ST) to lateral (VL-BF) co-contraction index ration during SLS task variables between study groups during pre-test (p>0.05), nor during the post-test variables between the study groups (p>0.05). Descriptive data of results in the medial (VM-ST) to lateral (VL-BF) co-contraction index ration during SLS task are illustrated in Table 5-26.

Table 5- 26: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the medial (VM-ST) to lateral (VL-BF) co-contraction index ration during SLS task.

Task	Medial (VM-ST)/ Lateral (VL-BF) CCI Ratio		
SLS	Mean	SD	P
Cont gp Pre	1.03	0.7	0.19
Cont gp Post	0.90	0.82	
Mean Diff	0.13	0.25	
Walk gp Pre	1.28	1.03	0.73
Walk gp Post	1.25	0.85	
Mean Diff	0.03	1.46	
WE gp Pre	0.94	0.42	0.28
WE gp Post	1.31	0.96	
Mean Diff	0.35	1.07	

Single leg squat (SLS), Medial knee muscles the Vastus Medialis and Semitendinosus (VM-ST), Lateral knee muscles the Vastus Lateralis and Biceps Femoris (VL-BF), Co-contraction index(CCI), control group (cont gp) ,walking group (Walk gp),walking and exercise group (WE gp), Pre (Pre-test) and Post (Post-test).

5.6.7 Centre of pressure excursion (CoP-Excursion).

In the control group, there was no significant change (Mean difference ± SD: 13.45±30 mm, p=0.18), in the range of motion of cop-excursion in comparison to the baseline values. In the walking group after wearing the AposTherapy system, there was significant reduction (Mean difference ±SD: 55.20±37.85 mm, p=0.001), in the range of motion of cop-excursion in comparison to the baseline values. In addition, the effect size calculated was d=1.24, which is considered large effect (Cohen et al., 1988). In the walking and exercise group participants after wearing the AposTherapy system alongside the additional exercise, there was significant decrease (Mean difference ±SD 22.18± 29.14mm, p=0.03), in the range of motion of CoP-excursion in comparison to the baseline values. In addition, the effect size calculated was d=0.51, which is considered moderate effect (Cohen et al., 1988).

There was no significant difference in the range of motion of CoP variable between study groups during pre-test (p>0.05). However, when observing the post-test analysis of data between three study groups there was significant difference between the control group and walking group variables(p<0.05). Furthermore, the control group and the walking and exercise group also showed significant difference regarding their post-test variables (p>0.05). Descriptive data of results in CoP-Excursion are illustrated in Figure 5-6 and Table 5-26.

Table 5- 27: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the CoP-Excursion values in three study group.

Task	CoP-Excursion			
SLS	Mean(mm)	SD(mm)	P	Effect size
Cont gp Pre	45.09	27.63	0.19	
Cont gp Post	35.63	13.35		
Mean Diff	9.43	30.97		
Walk gp Pre	73.16	42.57	0.001	1.24
Walk gp Post	17.95	8.03		
Mean Diff	55.21	37.85		
WE gp Pre	41.81	30.56	0.03	0.51
WE gp Post	19.63	7.79		
Mean Diff	22.18	29.14		

Centre of pressure (CoP), control group (cont gp), walking group (Walk gp), walking and exercise group (WE gp), Pre (Pre-test), and Post (Post-test

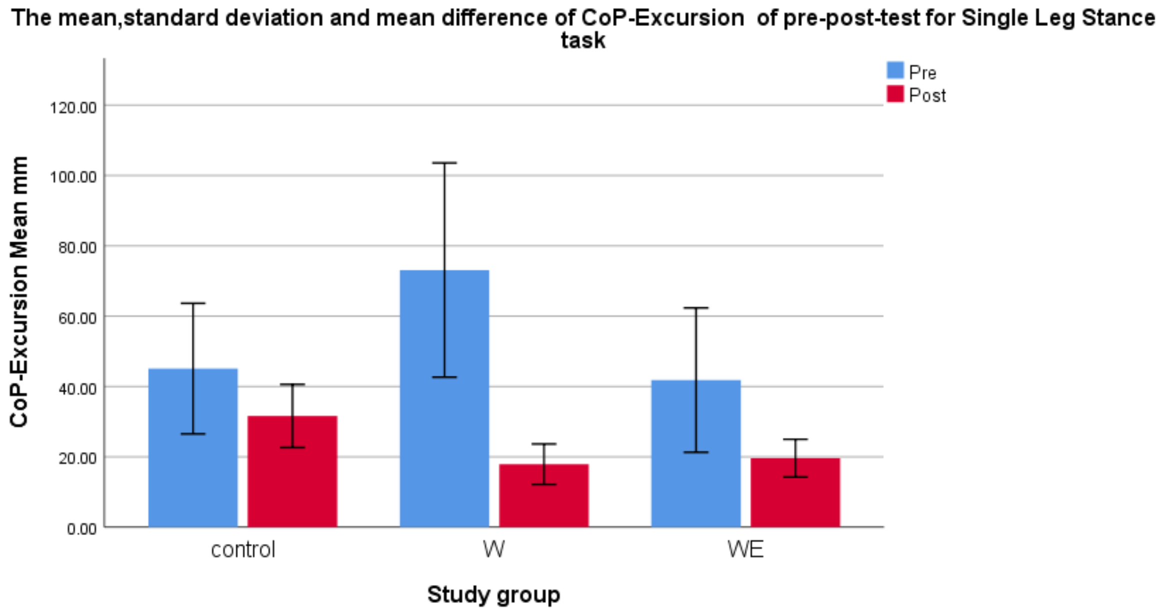


Figure 5-7: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the CoP-Excursion of pre-and post-test for Single Leg Stance task. Y –axis Cop Excursion (mm) and X-axis Sudy groups.

Based on criteria by Cohen et al. (1988), this would conclude the walking group had higher effect then the walking and exercise group as the effect size of the walking group of (d= 1.24) was larger than effect size of walking and exercise group of (d=0.51) which was considered moderat (Cohen et al., 1988).

5.7 Discussion.

The objective of this chapter was to understand whether employing the AposTherapy system would alter the risk factors associated with anterior cruciate ligament injury. The device was used by two of the groups with the third group not using any device. The discussion will follow by assessing each hypothesis in turn.

5.7.1 Postural stability.

> Hypothesis 1: There is no significant difference in postural stability before and after the AposTherapy intervention and between the intervention groups and control group during Single leg stance task.

Several studies that have incorporated balance and proprioceptive training have demonstrated improvements in postural stability, which has been postulated to relate to potential risk for lower limb injury (Olsen et al., 2005; Holm et al., 2004; Paterno et al., 2004). Landry et al. (2010) investigated the effect of MBT (M. Walk model, Masai. Barefoot Technologies, Switzerland), reporting that postural instability did decrease between Pre-post-test visits for participants who used unstable footwear only. This may imply that lower limb muscular coordination may have been improved to reduce postural stability (Landry et al., 2010). Furthermore, research work has documented that the incorporation of unstable footwear may induce positive biomechanical effects (Nigg et al., 2006; Taube et al., 2008; Price et al., 2013; Farzadi et al., 2017).

The AposTherapy system in the current study showed potential ability to improve postural stability measures. This was demonstrated by a significant reduction observed in CoP-excursion measures at post-test assessment in both intervention groups. The effect size of the walking group (d= 1.24) was larger than the effect size of the walking and exercise group (d=0.51) based on criteria by Cohen et al. (1988) who have described the values of effect size in three ranges (d=0.2 is a small effect size., d=0.5 is a moderated effect size., d=0.8 or more is large effect size). This would seem to indicate that the walking group experienced a higher effect than the walking and exercise group. This observation may be explained because participants in the walking-only group did not have any additional exercise to perform, using only the AposTherapy system as often as they felt comfortable using it. In fact, the majority even started to wear it whilst going outside their home and work places, which may have resulted in better effects overall. The results of systematic reviews and meta-analysis studies indicate that the prophylactic effectiveness of NMT is influenced by the dosage of NMT, level of compliance and the type of exercises (Van Reijen et al., 2016; Sugimoto et al., 2012,2015; Sadoghi et al., 2012). Furthermore, investigators have reported an inverse response association between NMT volume and ACL injury risk reduction (Nessler et al., 2017; Sugimoto et al., 2014; Sadoghi et al., 2012). Therefore, the dosage is definitely a crucial element to take into consideration for the development and successful implementation of NMT in intervention programs.

Several studies that incorporated balance and proprioceptive training have demonstrated improvements in postural stability as they reported that a lack of postural stability was related to potential risk for lower limb injury (Olsen et al., 2005; Holm et al., 2004; Paterno et al., 2004). Therefore, unstable training devices such as wobble boards have demonstrated the ability to decrease musculoskeletal injuries in lower limbs in younger and older populations; this type of training results in enhancing neuromuscular coordination and improving the proprioception of lower limbs. It may even strengthen select muscles (Landry et al, 2010; Emery et al, 2010; Waddington et al., 2004). The unstable footwear devices have been developed to mimic a stimulating effect on lower extremity neuromuscular control. Similar to the wobble board, with the primary purpose of strengthening and improving activation patterns that may be relatively under-utilised and inactive whilst wearing normal footwear (Landry et al., 2010; Farzadi et al., 2017).

Landry et al. (2010) investigated the effect of MBT (M. Walk model, Masai. Barefoot Technologies, Switzerland), reporting that postural instability did decrease between Pre-post-test visits for participants who used unstable footwear only. This may imply that lower limb muscular coordination may have been improved to reduce postural stability (Landry et al., 2010). Furthermore, several research works documented that the incorporation of unstable footwear may induce positive biomechanical effects (Nigg et al., 2006; Taube et al., 2008; Price et al., 2013; Farzadi et al., 2017). They demonstrated an increase in lower limb muscle activity levels when using unstable footwear, which may justify using unstable footwear as a training method to improve lower limb muscle recruitment patterns and strength (Farzadi et al., 2017; Horsak et al., 2013; Demura et al., 2012).

One proposed concept of footwear design in unstable shoe construction aims to induce controlled instability whilst standing and walking, for example by using balance pods centered in the forefoot and heel region (e.g. Reebok Easy Tone) or rocker-bottom (e.g., Masai Barefoot Technology) (Plom et al., 2014). Such shoe designs reportedly have a positive health effect in terms of increasing lower limb muscular activation during locomotion and/or decrease of joint loads (Horsak et al., 2015). Different footwear designs have demonstrated that they could generate the biomechanical manipulation commonly employed for this purpose by acting as an interface between the ground and foot (Haim et al., 2012). Thus, the footwear may manipulate sensory feedback information originating from the plantar surface of the foot generating those stimuli (Khoury et al., 2015). The concept behind these designs is to introduce a controlled destabilisation which would challenge lower limb joint dynamic stability and balance control (Farzadi et al., 2017). This alteration in lower limb muscle recruitment pattern may allow users to develop adequate motor control to protect their lower extremity joints from potentially hazardous loads during functional activities (Khoury et al., 2015; Anderssion et al., 2013; Chmielewski et al., 2005; Fitzgerald et al., 2000).

In a study by Price et al. (2013) the author investigated the effect of commercially available unstable footwear on single leg balance test in 15 healthy physically active females. The study compared four different types of unstable footwear: Masai Barefoot Technology (MBT), Reebok Easy-Tone, FitFlop, and Skeckers Tone-ups, all with control footwear which was an comnerial available unstable sandle. 3D motion with synchronized EMG and kinetic data were collected. The lower limb muscle activation, kinematics and centre of pressure trajectory were investigated, as participants performed walking gait during the stance on their right leg. The authors reported an overall minimal difference between the four unstable footwear samples and the study control footwear. The study also reported that centre of pressure data demonstrated no consistent difference between the stable control and the unstable Sandals.However, MBT footwear decreased the (A-P) range of centre of sway amplitude in the (A/P) direction which may have reflected in an increase in limb instability. Moreover, muscle activation was increased when participants wear the unstable MBT footwear, demonstrating significant differences apparent in the gastrocnemius, tibialis anterior and soleus muscles. The study only examined the right side which was the dominant side for most participants. It would be interesting to know how the non-dominant side behaved when wearing unstable shoes, given that females are at higher risk of sustaining an ACL injury on the supporting limb, which is usually the non-dominant one (Brophy et al., 2010). Nonetheless, the study only examined participants during standes phase during walking gait, and it would be expected that dynamic tasks would produce greater differences in instability variables. Nevertheless, the authors in this study brought up an important point by expressing the limitations of the footwear being investigated being customisable so as to be recommended to specific individuals. In addition, the study showed the unstable footwear used in the study only increased instability in one motion plane (sagittal plane), which has more to do with the nature of its design.

A number of studies have investigated the effect of unstable footwear on balance and lower limb mechanics and muscular activity pattern, highlighted the improvements in the lower limb proprioception, muscle coordination and joints motion and loads (Farzadi et al., 2017; Plom et al., 2014; Elkjaer et al., 2011; Landry et al., 2010). Hence, unstable footwear was introduced as a device to be used in training, with the proposal to combine stability with daily locomotion (Farzadi et al., 2017; Price et al., 2013; Kaelin et al., 2011; Nigg et al., 2006). Several kinds of unstable footwear have been developed during recent years, showing favorable outcomes of functional activity and in pain reduction (Khoury et al., 2015; Elbaz et al., 2010; Erhart et al., 2010; Thorstensson et al., 2007; Roddy et al., 2005). Each unstable footwear design utilised different strategies, including multi-density rocker sole and balance pods, with the aim of impelling controlled instability to enhance lower limb muscles during daily activities (Farzadi et al., 2017).

In the current study the AposTherapy system has demonstrated the ability to significantly improve postural stability for female recreational athletes after a six-week period of intervention. Moreover, it has shown the ability to increase instability when compared with normal footwear as demonstrated in the feasibility study in Chapter Four. Hence, it is logical to consider using this in NMT programs as an unstable device, which may be useful for its ability to be dynamically manipulated to suit individual needs.

In summary, there was a reduction in CoP-excursion variables reflecting improvements in the degree of postural stability. In this study, there was considerable improvement in participant's postural stability in the walking group and in the walking and exercise group. Moreover, there was a significant difference in both intervention groups when compared with the control group. However, it appears that a higher degree of stability was produced when using the AposTherapy system without any additional exercise. Therefore, the null hypothesis was rejected, as the results showed significant improvements in postural stability in both intervention groups, with a noticeably a better effect size in the walking-only group.

5.7.2 Kinematic and kinetic outcomes.

- Hypothesis 2: There is no significant difference in maximum knee valgus angle before and after the AposTherapy intervention and between the intervention groups and control group during Single leg squat task (SLS) and Single leg landing task (SLL).
- Hypothesis 3: There is no significant difference in maximum knee valgus moments before and after the AposTherapy intervention and between the intervention groups and control group during Single leg squat task (SLS) and Single leg landing task (SLL).

Several studies have documented that female athletes have been reported as increasing frontal plane motion and moments during high-risk athletic movements when compared with male athletes (Ford et al., 2011; Hewett et al., 2006; Kernozek et al., 2005; Mclean et al., 2004; Ford et al., 2003). In addition, female athletes reported high dynamic knee valgus during common sport movements, which had been observed as a potentially high-risk movement strategy (Myer et al., 2010; Withrow et al., 2006; Hewett et al., 2005; Olsen et al., 2004).

The results of this study showed that the maximum knee valgus angle reduced with no significant change between the intervention groups (walking group, walking and exercise group). However, a significant reduction was found in the walking group during a SLL task (d=0.53). The mean difference was 3.42°, which may be considered clinically significant as it exceeded the MDD values of 2.30° knee valgus angles during a SLL task, which were previously reported in the reliability study in Chapter Three section 3.2.7.2. In addition, it also was more than the standard of error of measurement of 2.5° knee valgus joint angles during the SLL from a similar height to the stand used in current study (Ortiz, et al., 2007). There was a non-significant reduction in the knee valgus angle in the walking group during the task SLS shown 26.7% reduction in comparison with their baseline values. In the walking and exercise group, non-significant reductions were seen in the knee valgus angle during both SLL and SLS functional tasks, showing average reductions of 38.3% and 12.4%, respectively in comparison with their baseline values.

Knee valgus moments have been documented as directly contributing to lower limb dynamic valgus and knee joint loads at a sensitivity of 78% and specificity of 73% for predicting NCACL injury risk (Hewett et al., 2005). Interestingly, the knee valgus moment values in the walking and exercise group demonstrated small increases during the SLL and SLS tasks, with average increase of 7.55% and 4.10%, respectively, on average when compared with their baseline values. This could be explained when examining other lower limb biomechanical variables, such as ground reaction force (GRF) values in the walking and exercise group which showed a minor increase during SLL and SLS by 0.78% and 0.44%, respectively, on average when compared with their baseline values. Nonetheless, this may be related to the structure of the intervention group as the added work-out exercise resulted in a more specific focus on the hip musculature. When comparing the intervention groups, there was no difference between the groups but the knee valgus moment values for the walking group showed a larger decrease in knee valgus moments during both functional tasks, but more in the SLL and SLS task, with an average reduction of 36.4% and 21.4% in comparison with their baseline values. This could be due to the nature of the intervention of each group. As the walking group was more focused on the muscles surrounding the knee joint, whereas, the walking and exercise group focused more on the hip abductors.

The outcomes demonstrated in the walking group in the current study may suggest that it could be attributed to the perturbation training and alignment adjustment element that the AposTherapy system delivered without any additional exercise influence. Intervention programs which incorporate proprioception and balance training use the principle that parts of the body act as a system of chained links, whereby the whole limb is regarded as one kinetic functional unit, starting from the foot through the body segments (Khoury et al., 2013; Haim et al., 2008). The proposed mechanism would infer that altering the instantaneous CoP trajectory of the foot might manipulate the orientation of this torque, resulting in altering knee joint motions and moments (Haim et al., 2008,2010).

Footwear-generated (AposTherapy system) biomechanical manipulation has been proposed as altering the trajectory of the centre of pressure. Two previous studies analysing the kinetic outcomes of the AposTherapy system on a population of healthy males demonstrated the ability to allow for controlled manipulation of the CoP during locomotion (Khoury et al., 2015). The manipulation of knee and ankle sagittal moments could be achieved by a controlled shift of the CoP sagittal plane (i.e., from posterior to anterior), which was significantly correlated to with knee extension and dorsiflexion torques during the stance phase (Haim et al., 2010). Likewise, in a previous study, the biomechanical elements were shifted on medial and lateral translation (i.e., medial to lateral), significantly correlated changes in the knee moments at the frontal plane with the external knee adduction moments (EKAM) during the stance phase (Haim et al., 2008). The study showed that EKAM could be manipulated as reductions in EKAM during the lateral coronal axis configuration, with an increase in EKAM with medial coronal axis configuration (Haim et al., 2008). Thereby, control manipulation of the device element can significantly alter the foot centre of pressure (CoP) location (Khoury et al., 2013, 2015), affecting the kinematic and kinetic parameters of gait for both osteoarthritis patients and healthy individuals (Khoury et al., 2015; Haim et al., 2011, 2012).

The outcomes of the study showed that both intervention groups showed promising results in terms of frontal plane biomechanical risk factors for NCACL injury in female athletes. Interestingly, a better outcome was observed at the knee joint frontal plane in the walking group, especially at knee valgus motion while performing the SLL task. This finding was significant as it could be mainly related to the nature of the waking group’s intervention as they were using the AposTherapy system during walking and while doing their daily activities with no added exercise, which may have caused an accumulation affect. Also, as they increased the time with the device each week, they felt comfortable with it, resulting in potentially greater improvement of neuromuscular activation of quadriceps and hamstring muscles.

When looking at the other secondary outcomes, participants in the walking and exercise group showed improvement in the frontal plane hip joint variables, a significant reduction in hip adduction moment was observed during the performance of SLL and SLS functional tasks (d=2.28 and d=0.41, respectively). The walking and exercise group showed non-significant reduction. However, a large reduction by 60% in comparison with their baseline values in hip adduction angle in particular during the SLL task. This improvement in the frontal plane at the hip joint level in participants in the walking and exercise group may be attributed to the nature of the study intervention, with the added exercise elements improving the hip abductor muscle activation pattern and strength that could be related to the incorporation of multiple squatting to a high level of difficulty (Hewett et al., 2016; Ortiz et al., 2010).

Biomechanical studies have documented that when hip control is poor, in particular the Gluteus Medius muscle, the hip tends to move more into adduction when landing (Zeller et al., 2003; Winter et al., 1995). Once the hip moves into adduction, the femur will rotate internally, and the knee joint will move towards valgus. Thus, increasing the stress on the ACL a combination of these events places female athletes in a “position of no return”, as mentioned by Ireland et al. (1999). Nevertheless, previous studies suggested that improved frontal plane control at both the hip and ankle may be necessary to reduce ACL injury risk (Myer et al., 2006; Myklebust et al., 2005; Beynnon et al., 2004). These data support the previous documented effect of NMT on improving mechanics during execution of functional activities in the frontal plane (Ortiz et al., 2010, 2008).

The knee flexion angle and sagittal plane moments showed minor changes in the exercise group, while in the walking group, there was a slight increase in the knee flexion angle and moment values during the SLL and SLS tasks, in agreement with the observations made by Cochrane et al. (2010) who reported that participants who participated in balance training only showed improvement in knee valgus, flexion, and internal rotation when compared with groups who utilised free weight and machine weight exercise (Cochrane et al., 2010). The author explains that strength programs consist of only exercises working in the sagittal plane, whereas a balance training program challenges neuromuscular coordination in all three motion planes, thus explaining its better effect (Cochrane et al., 2010). On the other hand, walking and exercise group participants demonstrated a slight decrease in knee flexion angle and moments during both study functional tasks, except for knee valgus moments during SLS tasks which may be related to the nature of the intervention, which is also in agreement with the findings of Cochrane et al. (2010) who found that an increase in the applied knee flexion moments may have been moderated by improvements in valgus loads.

Studies have demonstrated that female athletes tend to land in a higher erect position while landing from a jumping maneuver (Cortes et al., 2011; Blackburn and Padna, 2009). This landing pattern in females has been documented to be associated with greater GRF, thus may result in more strain placed on the ACL (Blackburn and Padna, 2009). On the other hand, male athletes have been reported to demonstrate a greater knee flexion and ankle dorsiflexion when landing compared with female counterpart, thus resulting in decreasing GRF (Cortes et al., 2007). Moreover, DeVita and Skelly (1992) reported that when landing high knee flexion angle was coupled with a softer landing leading to reduction in GRF compared with erect landing in low knee flexion angle. Furthermore, Hewett et al. (2005) documented a relationship between ACL injury risk and peak GRF among adolescent female volleyball, football and basketball athletes. The author reported that female athletes who had an ACL injury showed 20% greater peak GRF when compared to healthy control. A study by Fong et al. (2011) investigated the relationship between landing biomechanics and ankle dorsiflexion in thirty-five male and female healthy participants. The authors reported a significant correlation between GRF and ankle dorsiflexion and knee flexion. The study outcomes suggested that the greater knee flexion and ankle dorsiflexion and smaller GRF when landing were related with reduced ACL injury risk as a result of decreasing the loads that the lower limb must absorb (Fong et al., 2011).

Moreover, studies have reported that when the knee flexion angle is less than 30°, the quadriceps muscle contraction may increase the strain on the ACL (Nagano et al. 2011; Distefano et al., 2009; Beynnon et al., 1995). Nevertheless, hamstring muscle contraction at this knee flexion angle cannot reduce the strain on the ACL because the hamstring muscle meets the tibia at a smaller angle (Pandy et al., 1997). However, when the knee flexion angle is greater than 60°, the quadriceps muscle contraction would not put a strain on the ACL during sporting activities (Nagano et al. 2011). Therefore, the knee flexion variables may not be influential as knee flexion angle was not less than 64° during SLL task and not less than 74° for both intervention groups, which are higher than the previously proposed hazards values.

As previously mentioned the maximum knee valgus angle was only significantly decreased in the walking group during the SLL task. Moreover, there was significant difference in walking intervention group when compared with the control group in regarding knee valgus angle and knee moment during SLL task. On the other hand, the outcomes of the walking and exercise group were not encouraging with a negative trend towards an increase in knee valgus loads during SLL tasks. However, there was no significant difference between the walking and exercise intervention group and control group in knee valgus moment during SLL task. Moreover, no significant different between the intervention groups and control group in either knee valgus motion nor moment during SLS task was indicated in this study. Furthermore, there was a group-selective improvement in the frontal plane. The walking group demonstrated a significant decrease in knee valgus angle and reductions in knee valgus moments during the SLL functional task. In addition, there were also non-significant reductions in knee valgus angle and moment during the SLS functional task. Additionally, the walking and exercise group demonstrated significant reductions in hip adduction moment and non-significant reductions in hip adduction angles. All these changes could indicate improvements in dynamic knee joint stability and lower limb valgus.

In summary the second null hypothesis was partially rejected regarding the use of the ApосTherapy system without the needed for any added exercise which significantly reduce knee valgus angle. In addition, there was significant differences between the walking group and control group in knee valgus, which might help to withstand knee valgus loads during sport activities for the walking group. On the other hand, the second null hypothesis was partially accepted regarding the walking and exercise group with non-significant reduction documented for knee valgus angle. In regarding the third null hypothesis it was partially rejected because there was no significant change in knee valgus moment reported by both study intervention groups. However, there was significant differences between the walking intervention group and control group in knee valgus moment.

5.7.3 **Muscular co-contraction.**

- Hypothesis 4: There is no significant difference in muscle co-contraction of the medial side of the knee (Vastus Medialis and Semitendinosus) before and after the AposTherapy intervention and between the intervention groups and control group during Single leg squat task (SLS) and Single leg landing task (SLL).
- Hypothesis 5: There is no significant difference in muscle co-contraction of the lateral side of the knee (Vastus Lateralis and Biceps Femoris) before and after the AposTherapy intervention nor between the intervention groups and control group during Single leg squat task (SLS) and Single leg landing task (SLL).

Co-contraction of the muscles around the knee joint at a sufficient recruitment pattern would compress the knee joint enough to withstand valgus load by articular contract forces, which may protect the ACL from high loads (Mohr et al., 2017; Hall et al., 2015; Hewett et al., 2005). The co-contraction of the quadriceps (Q) and hamstrings (H) not only protects the knee joint against excessive anterior drawer but also helps it withstand excessive dynamic lower limb valgus (Hewett et al., 2005; Besier et al., 2003). The co-contraction index is identified as one strategy of the neuromuscular system to stabilise a joint (Horsak et al., 2015; Lewek et al., 2005). One way to withstand applied valgus-varus loads at the knee joint is to generate generalised co-contraction of all the muscles around the joint. Furthermore, another method is to selectively activate the muscles with the appropriate moment arms to resist those loads (Letafatkar et al., 2015; Palmieri–Smith et al., 2009). Both generalised and selective co-contraction strategies can be considered effective in reducing stress on the ACL (Palmieri–Smith et al., 2009; Hewett et al., 2005). Selective activation of the muscles with the mechanical ability to counter the applied valgus-varus loads, namely selective co-contraction of the lateral musculature of the knee joint, which has a valgus moment arm, and selective activation of the medial musculature of the knee joint, which has a varus moment arm, are neuromuscular strategies that have been found to stabilise the knee joint in the frontal plane in the presence of isometric loads (Letafatkar et al., 2015; Palmieri–Smith et al., 2009).

During the single leg landing tasks there was non-significant improvement in medial musculature co-contraction index of the knee joint (VM-ST) in both intervention groups during feedback motor control phase (31.8% and 3.6% in the walking and walking and exercise group, respectively, on average in comparison with their baseline value). Furthermore, during the feed-forward motor control phase there was increase of 24.8% in the walking and exercise group and reduction of 12% in the walking group on average in comparison with their baseline value. In regard the lateral knee joint muscular co-contraction index (VL-BF) during feed-forward motor control phase showed reduction by 3.6% for the waking group. However, a slight increase by 20.8% for the walking and exercise groups, on average in comparison with their baseline value. Interestingly, in the medial knee (VM-ST) to lateral knee (VL-BF) co-contraction index ratio during feed-forward motor control phase showed improvement in both intervention groups by 12% and 21.4%, respectively, for the waking group and walking and exercise group, on average in comparison with their baseline value. On the other hand, the in medial knee (VM-ST) to lateral knee (VL-BF) co-contraction index ratio during feedback motor control phase showed improvement in walking group by 30% but with a slight drop by 12% for the walking and exercise group, on average in comparison with their baseline value.

The walking group showed a non-significant decrease in values of VL-BF co-contraction index during feedback motor control phase by 26.3 %MVIC which was more than the VL-BF co-contraction index during feedback motor control phase MDD values of 11.91 %MVIC reported in reliability study at Chapter Three in section 3.2.7.3. Moreover, there was significant difference in walking group when compared with the control group regarding values of VL-BF co-contraction index during feedback motor control phase during SLL task. In addition, walking and exercise group showed a non-significant increase in values of VM-ST co-contraction index during feedforward motor control phase which was 11.8% MVIC, which was more than the VM-ST co-contraction index during feedforward motor control phase MDD values reported in the reliability study at Chapter Three in section 3.2.7.3. Furthermore, there was significant difference in walking group when compared with the control group regarding values of VM-ST co-contraction index during feedforward motor control phase during SLL task. However, all these values were non-significant in comparison with the baseline values. The differences which were greater than the MDD values from the reliability study in Chapter Three in section 3.2.7.3, but the low sample size and high variability in the sample, which meant lack of significance was found.

While during the SLS function task, there were non-significant improvements in the post-test values of medial to lateral knee muscular co-contraction ratio in the walking and exercise group only with values of 0.35. This was higher than the MDD values of 0.29 reported at the reliability study in Chapter Three in section 3.2.7.3. However, the high variability and insufficient sample size might attribute to the non-significance of outcome. This may reflect the slow and low dynamically demanding nature of the SLS requiring good hip abductors muscle activation couples with quadriceps and hamstrings muscle activation, which may have been achieved by adding exercise in the walking and exercise group.

The current study showed similar patterns of improvements in the medial knee (VM-ST) and lateral knee (VL-BF) co-contraction index during the feed-forward and feedback motor control phases while performing single leg landing tasks which was demonstrated in a study by Letafatkar et al. (2015). The study by Letafatkar et al. (2015) evaluated the affect of performing NMT program focused on perturbation-based training. The author reported an increase in co-contraction index of medial knee (VM-ST) from 20.55 ±1.31 to 25.93 ± 1.45 %MVIC during feedforward motor control phase and from 22.92±1.27 to 28.32±1.52 %MVIC during feedback motor control phase. Whereas, the lateral knee lateral (VL-BF) muscles showed an increase in the co-contraction index from 22.33±1.19 to 29.10±2.57 %MVIC during feed-forward motor control phase and from 46.73±2.27 to 54.66±3.77 %MVIC during feedback motor control phase. However, even though the finding were reported to be significant, which may be attributed to high intensive long duration intervention program with sessions ranging between 60-120 min session, it would not be realistic for most coaches or/and athletes to participate in (Lim et al., 2009; Sugimoto et al., 2014). In addition, the study sample size was sufficient which may have attributed to significance of the study outcomes.

Various muscle recruitment strategies have been adapted to withstand applied valgus-varus loads at the knee joint, one recruitment strategy is by generating generalised co-contraction of all the muscles around the joint. On the other hand, another recruitment strategy is to selectively activate the muscles to resist those loads (Letafatkar et al., 2015; Palmieri–Smith et al., 2009). Both generalised and selective co-contraction strategies can be considered effective in reducing stress on the ACL (Palmieri–Smith et al., 2009, Hewett et al., 2005). Selective activation of the muscles with the mechanical ability to counter the applied valgus-varus loads, namely selective co-contraction of the medial musculature of the knee joint, would support the knee to withstand high valgus loads, whereas, the lateral musculature of the knee joint, would support the knee to withstand high varus loads during demanding activities , this may be considered neuromuscular strategies that have been found to stabilise the knee joint in the frontal plane in the presence of dynamic loads (Letafatkar et al., 2015; Palmieri–Smith et al., 2009).

The outcomes of the walking and exercise group during the feedforward motor control phase demonstrated generalised muscular control improvement showing an increase in medial muscular activation of the knee joint and in the lateral musculature activation of the knee of joint are in general agreement to the ones in Letafatkar et al. (2015) study. There was a general increase in both the medial knee (VM-ST) and lateral knee (VL-BF) co-contraction index by showing an average increase of 24.37% and 20.82%, respectively, in comparison to their baseline values in the walking and exercise group. This may be related to both interventions being based on exercise whilst using the unstable device; meanwhile, in the current study, participants in walking group showed a selective muscle recruitment pattern improvement in the medial musculature of the knee joint and reduction in the lateral musculature, which may compensate for each other. Participants in the walking groups demonstrated different muscle recruitment pattern than those in the walking and exercise groups. This finding may be related to the dosage effect as the walking group walked with the device during daily activities without time taken for additional exercise.

In summary, this current study postulated that the incorporation of the AposTherapy system may induce positive changes in the muscle recruitment pattern of the lower limbs in the walking and walking and exercise groups. However, no significant changes were observed. Therefore, in conclusion, both the fourth and fifith null hypotheses were accepted because there was no significant change within the intervention group, nor between the study intervention groups and control group, in the muscular co-contraction index of the medial and lateral musculature of the knee joint and medial to lateral musculature co-contraction ratio during the functional tasks.

5.8 Limitations.

The results of this study may be subject to several limitations. Firstly, the study outcomes can only be generalised to adult female recreational athletes only. These findings cannot be generalised to other female athlete populations of a younger age and different skill levels. Secondly, unbalanced footwear previously demonstrated the ability to stimulate activation of the large extrinsic foot muscles crossing the ankle joint complex, thus increasing the activity of the gastrocnemius and tibialis anterior muscles (Goryachev et al., 2011; Nigg et al., 2006). Nevertheless, the medial and lateral Gastrocnemius would be important in future studies as they have been documented to influence the knee dynamic stability during functional activities (Maniar et al., 2018; Junge et al., 2015). Thirdly, the investigation only included the observation of short-term effects of the AposTherapy intervention, it is not known how long the effect of intervention will last for. However, it could be argued that the athletes could continue using the device during the pre-season and in-season because it has a low intensity, simple nature. Fourthly, the effect of the menstrual cycle was not taken into consideration and this may deserve to be taken into consideration in future studies with some studies proposing the potential effect of female hormones on muscles mechanical properties especially during the menstrual cycle (Herzberg et al., 2017; Casey et al., 2014; Lefevre et al., 2013; Smith et al., 2012). Fifthly, the use of participant follow-up sheet (number of sessions and session duration) is appropriate method for monitoring the participant adherence rate. However, this method could be exposed to recall bias; it would have been more objective if physical activity sensors were implemented into the AposTherapy system this would be a more accurate method to monitor participant adherence rate. Finally, due to the high cost of the AposTherapy system and limited funds the sample size of this study was restricted and the likelihood for some of the null results seen is down to the low power of the study. Additionally, owing to logistical complexity and limited funds, we could not increase the degree of perturbation by up-grading to pods with a greater degree of convexity to replace the ones installed at the customisation session at the beginning of the study to progress the perturbation challenge, a step which may have improved the study outcomes. Further studies with a much larger sample size should be performed to investigate the long-term effect of AposTherapy intervention. The AposTherapy system is a highly costly biomechanical device. This may be a hurdle of implementing the AposTherapy system into large scale prevention program. However, it could be a beneficial option in rehabilitation programs for young active people who ruptured their ACL during non-contact mechanism and can be incorporated during the pre-operative or post-operative phase of their rehabilitation program to correct the predisposing biomechanical and recruitment pattern to reduce the risk of sustaining a second ACL injury.

5.9 Conclusion.

The literature review identified the gap between the laboratory results obtained with the neuromuscular training program and the actual effect on ACL injury risk outcomes in high-risk female athletes, which postulated a missing link between current published research and clinical applications for the prevention intervention program. The time demand and complexity can be daunting for athletes and coaches implementing these programs at a larger scale. The aim of this study was to evaluate the effect of incorporating the AposTherapy system on lower limb postural stability, kinematics, kinetics, and electromyography measures in high-risk recreational female athletes.

The outcomes of this study demonstrated the potential ability of the AposTherapy system to functionally improve postural stability during Single-Leg Stance which was observed in both intervention groups, with greater effect size in the walking group. In addition, only participants in the walking group demonstrated reduction in knee valgus angle during single leg landing tasks coupled with a strong trend towards reduction in knee valgus loads on the participant’s supportive lower limbs was a promising finding which may reduce the risk for non-contact ACL injury in the recreational female athletes population by using the

Apostherpy system during simple walking only intervention. The walking and exercise group demonstrated reduction in hip adduction loads, this was explained by improvement in hip musculararture. This could have proposed that the AposTherapy system supplemented with exercise may be beneficial to be introduced to post-surgery rehabilitation program for individuals who had total hip replacement. However, this would be beyond the scope of the present thesis.

Chapter Six: The role of incorporating AposTherapy system on lower limb biomechanics in recreational athletes with a high risk for second non-contact ACL injury at contralateral limb, after primary ACL Reconstruction: Pilot study.

6.1 Introduction.

The magnitude of the problem is clear, with a high incidence of a second NCACL injuries post- ACLR surgery, particularly in young active people (Paterno et al., 2015; Capin et al., 2017). Over the past decade, a growing body of literature has highlighted a higher rate of second ACL injury after ACLR (Hewett et al., 2016; Wiggins et al., 2016: Raines et al., 2017). Second ACL injury is a common and devastating knee injury among young athletes who return to athletic participation after primary ACLR (Capin et al., 2017; Raines et al., 2017; Webster et al., 2014; Paterno et al., 2014). It been documented that more than 50% of athletes are unable to return to pre-injury level of athletic performance after ACLR. (Ardern et al., 2011). In addition, between 50-100% will eventually develop premature osteoarthritis within 5 to 10 years' surgery (Oiestad et al., 2010).

Moreover, a number of long term studies with follow-up duration ≥ 10 years have reported the rate of the second ACL injury in patient who had primary ACLR to be between 23-27% (Drogset et al., 2006; Bourke et al., 2012; Morgan et al., 2016). High-risk populations include athletes participating in pivoting and cutting sports and female athletes. However, patients who previously sustained NCACL injury and had ACLR surgery showed higher risk of sustaining a second ACL injury (either graft failure or contralateral injury) compared with individuals who did not sustain primary ACL injury (Wright et al., 2011; Paterno et al., 2012,2015). In studies by Wiggins et al. (2016), and Paterno et al. (2012), both data indicated that nearly 1 in 4 young athletes (23%), who had ACLR and return to sports will go to sustaining second ACL injury at some point in their career and they are likely to sustain it early after returning to sports activities. This high rate of second ACL in young athletes who return to sports activates after ACLR which equals to a 30 to 40 times greater risk of an ACL injury compared with uninjured age and skill matched athletes (Wiggins et al.2016).

In a series of publications which investigated the risk of sustaining a second ACL injury in individuals who sustained a previous ACL injury, and reported after follow up period of 5 years, 10 years, and 15 years on athletes post ACLR, reported that second ACL injury rates were 12%, 27%, and 31%, respectively (Salmon et al., 2005; Pinezewski et al., 2007; Leys et al., 2012). In a prospective study by Capin et al. (2017), 14 young female athletes were followed who were involved in jumping, pivoting, and cutting sports activities. The authors reported that seven athletes sustained a second ACL injury which represented 50% of study population within 20 months (13.4±4.9 months) after ACLR, after they were medically cleared to return to sports participation. Furthermore, studies have showed that the majority of second ACL injury occurred at the contralateral knee (Paterno et al., 2014; Wright et al., 2011; Shelbourne et al., 2009; Keays et al., 2007). Paterno et al. (2014) documented that 29.5% of athletes suffered a second ACL injuries within 24 months of return to sport with 20.5% happening on the contralateral injury with 9% sustaining a graft failure at the ipsilateral side. In a systemic review of 5-year follow-up outcomes after ACLR, Wright et al. (2011), reported a 17.2% second ACL injury rate, with a greater percentage sustaining a contralateral ACL injury (11.8%) and (5.4%) at the ipsilateral graft failure.

The mechanism of this high rate of second ACL injury after ACLR is likely multifactorial inclusive of unresolved preoperative risk factors (Paterno et al., 2010; Di Stasi et al., 2015; Hart et al., 2016; Nagelli et al., 2017). Residual impairment in the time of returning to sports was documented (Mattacola et al., 2002; Schmitt et al., 2012). Hence, there is a tendency of many athletes to develop compensatory patterns, which increase the stress on the uninjured (contralateral) limb when returning to sports (Ernst et al., 2000; Paterno et al., 2007, 2012), especially if the uninvolved limb also had the same predisposing risk factors as the injured limb (Hewett et al., 2016; Paterno et al., 2010). The current evidence has identified modifiable predictive factors of second ACL injury after ACLR which include biomechanical and neuromuscular measures as well as altered posture stability (Capin et al., 2017; Raines et al., 2017; Leys et al., 2012; Paterno et al., 2010). In a study by Pollard et al. (2015) observed female athletes who had ACLR. The authors observed an increase movement variability during side step cutting manoeuvers, which was more likely a result of altered neuromuscular control resulting in poor frontal plane kinematics. Several investigations have identified that individuals who had ACLR demonstrated altered knee kinematics and kinetics during dynamic tasks, even though they have participated in extensive rehabilitation post operatively and been allowed to fully participate in sports (Roewer et al., 2011; Delahunt et al., 2012; Stearns et al., 2013; DiStasi et al., 2015; Nagelli et al., 2017; Raines et al., 2017).

Several modifiable and non-modifiable risk factors for second ACL injuries have been reported to increase an athletes risk for a second ACL injury (DiStasi et al., 2013; Hewett et al., 2013). The non-modifiable factors including surgical technique, gender, and age of the patients can significantly impact the second ACL injury risk (Shelbourne et al., 2009; Hui et al., 2011; Magnussen et al., 2012; Paterno et al., 2012). Specifically, low graft inclination angles and the use of allografts may significantly increase an individual's risk for grafts rupture (Hui et al., 2011). In addition, the use of bone-patellar-tendon-bone autografts found to have high risk for second contralateral ACL injury, whereas, allograft found to have high risk for graft failure ipsilateral ACL injury (Leys et al., 2012). In addition, there is growing evidence for altered contralateral limb loading post-ACLR during sports-related activities (Paterno et al., 2010; Castanharo et al., 2011; Dehahunt et al., 2012), which may explain in part the increased rate of contralateral-limb ACL rupture in young active individuals (Brophy et al., 2012; Paterno et al., 2012).

The long-term benefits of an effective rehabilitation program may also be realised, both by the full restoration of functional performance and by the improved ability of these individuals to maintain and participate in lifetime activity without symptoms of knee injury (DiStasi et al., 2013; Melick et al., 2016). Paterno et al. (2010) prospectively observed 56 athletes with had primary ACLR who were screened at the time, and they were cleared medically to return back to athletic participation. The authors reported that one year from the time the participants resumed sports participation 13 of them sustained a second ACL injury (Paterno et al., 2010). The study demonstrated that a combination of biomechanical and neuromuscular factors, including postural stability, sagittal plane knee moments, frontal plane knee angles and transvers plane hip moments would have predicted the potential for second ACL injury with 92% sensitivity and 88% specificity (Paterno et al., 2010).

The previous results in the main study at Chapter Five have demonstrated promising outcomes after using the AposTherapy system with the proposal to reduce the neuromuscular and biomechanical risk factors in recreational female athletes who showed a high-risk movement pattern for primary ACL injury. However, due to the high cost of this biomechanical devise (AposTherapy system), it may not be ideal for large-scale implementation. Nevertheless, the flexibility and simplicity in using the AposTherapy system could encourage its use as a more time-efficient intervention component which may bring the required neuromuscular control enhancement effect and reduce high risk movement patterns to the post-ACLR rehabilitation programs. Thereby, it may be sensible to consider the AposTherapy system as a promising addition to the rehabilitation programs for post-ACLR patients. Thereby, encouraging more use of intervention programs to address risk mitigation for this serious injury. Therefore, it been suggested that the AposTherapy system may be a useful tool in intervention programs for preventing second ACL injuries in those athletes who had ACLR previously, and who been identified to have an imbalance in neuromuscular control, putting them at risk of second ACL injury. The objective for this study was to observe any alterations in the biomechanical risk factors associated with second ACL injuries (valgus knee angle and moment) and muscle recruitment pattern alteration in athletes who had primary ACLR with impaired neuromuscular control and postural stability.

6.2 Research question and hypothesis.

The research question determined whether the AposTherapy intervention would improve the lower limb dynamical alignment, muscle recruitment patterns and the dynamic postural stability following a six-week intervention period similar to the simple program used in the walking group in the main study in section 5.5 of Chapter Five (Main study). In general, it was hypothesized that the AposTherapy system would improve the neuromuscular control resulting in reduction in biomechanical risk factors for sustaining second ACL injury at the contralateral knee. Specific null hypothesis are as follows:

- Hypothesis 1: There is no significant difference in postural stability measures before and after the AposTherapy intervention during Single leg stance task.

- Hypothesis 2: There is no significant difference in maximum knee valgus angle before and after the AposTherapy intervention during Single leg squat task (SLS) and Single leg landing task (SLL).

- Hypothesis 3: There is no significant difference in maximum knee valgus moments before and after the AposTherapy intervention during Single leg squat task (SLS) and Single leg landing task (SLL).

- Hypothesis 4: There is no a significant difference in muscle co-contraction of medial side of the knee (Vastus Medialis & Semitendinosus) before and after the AposTherapy intervention during Single leg squat task (SLS) and Single leg landing task (SLL).

- Hypothesis 5: There is no significant difference in muscle co-contraction of lateral side of the knee (Vastus Lateralis & Biceps Femoris) before and after the AposTherapy intervention during Single leg squat task (SLS) and Single leg landing task (SLL).

- Hypothesis 6: There is a significant difference in patients reported outcomes (KOOS), before and after the AposTherapy intervention.

6.3 Method.

6.3.1 Participant.

Nine recreationally active male and female students were recruited from the University of Salford. The inclusion criteria required that individuals recruited in this study all had experienced a primary ACL injury and have had reconstruction surgery performed on their injured knee. They also had to have completed their rehabilitation program and been released by their surgeons to return to participate in sporting activities. In addition, all participants would be aged (18 to 39 years), and considered active in recreational sports consisting of more than 30 minutes of physical activity three times per week regularly over the past 6 months and known to participate in sports with high-risk maneuverers for NCACL injuries such as jump/landing and cutting movements. All participants were required to be free from lower extremity injuries for the last three months and without a history of ACL injury at the contralateral limb. All participants also had to have a Beighton score >4 for general laxity. Participants were excluded from the study if they had lower limb inequalities > 2 cm, a history of neurological or systemic disorders or a history of any injury (which was defined as any musculoskeletal complaint which stopped the participant from undertaking their normal exercise routine for more than 6 weeks prior to the start of the study), or were already participating in another injury prevention program. All participants should have had ACLR in the past 9 months at least and were permitted by their surgeon to participate in the study.

If the potential participant met the eligibility criteria, they were asked to visit the Human Performance Laboratory in Mary Seacole Building at University of Salford for screening to determine full eligibility in the study. The study was explained in full and the subject was asked to complete and sign a consent form before participating in the study. Individuals who agreed to take part in the study were initially assessed using 2D analysis to assess the frontal plane projection angle (FPPA) of their contralateral knee (non-ACLR knee) while performing a single leg squat task in a way similar to the the description previously mentioned in the Chapter Four (Feasibility study) in section 4.5.1.2 of Chapter Four. This was to determine whether they had insufficient neuromuscular control of the contralateral knee. In order to be eligible for the study, the individuals must have a 2D FPPA greater than 8.4° on their contralateral knee. The study population was one group who would be just using AposTherapy system during walking for 60 min period each day according to the standard intervention program instructions. All participants were seen for post-test after six weeks from the pre-testing. Research Ethics Committee of the University of Salford approved this study (HSR 1617-40).

ALL participants were recruited to the study, where after they were screened for a high dynamic valgus by 2D FFPA, six of these showed a high 2D FPPA at their contralateral knee (14.6±3.4°) and were identified as suitable participants for the study and they volunteered to participate in the study. During the intervention period one participant had to withdraw because they sustained an ankle injury during sports participation. The five participants managed to complete the study intervention, where they managed to achieve an adherence levels of around 90% of the study intervention program.

No statistical differences were observed in participants mass between pre-and post-test assessment sessions ($p>0.05$). In addition, no significant differences regarding the participants physical activity levels assessed according to Tegner activity scale (TAS) (Tegner et al., 1985) were evident. Participants sports activities included Football (3), Rugby (1), and Skiing (1).

Table 5- 28: Participants demographic data in Mean ±SD.

Parameters	Participants (5)
Height	171.6±9.65cm
Mass	70.6±14.29 kg
Age	26.2±2.16 years

6.3.2 Procedures.

6.3.2.1 Screening process: Two-Dimensional (2D) video capture.

An identical study protocol for the screening process with 2D video capture, which was conducted in feasibility study in section 4.3.2.1 of Chapter Four, was undertaken to identify individuals with high dynamic valgus. The average of the three trials was calculated for the contralateral knee (non-ACLR knee) and if participants recorded an average 2D FFPA greater than 8.4° they were included in the next stage of the study. For individuals who did not have a 2D FPPA greater than the inclusion criteria, they were thanked for attending the laboratory and informed that they were not eligible for the next stage of the study. Individuals who were included in the intervention trial entered the full study protocol, where firstly they were calibrated with the AposTherapy system on attending the laboratory for another session.

6.3.2.2 AposTherapy system calibration.

All participants had the same calibration process by senior technician from (AposTherapy.UK), as previously described in Feasibility study in section 4.3.2.2 of Chapter Four.

6.3.2.3 Three-dimensional (3D) motion analysis, EMG and CoP-Excursion data capture.

Participants followed the same collection procedure described previously in section 3.2.3 of Chapter Three, on the collection of the 3D, EMG and CoP-excursion measures.

6.3.3 Study tasks.

The study tasks adopted were the same as described at in section 3.2.3.3 of Chapter Three which were the single leg squat (SLS), single leg landing tasks (SLL) and Single-leg Stance task as. Each task was completed five trials at each testing session.

6.3.4 Conducting the tests.

6.3.4.1 Baseline data collection session.

The participants followed the same data collection procedure described previously at Chapter Five in section 5.3.4. Than conducted the test on the contralateral limb.

6.3.4.2 Follow-up data collection session.

After the participants finished the six-week intervention program, the same biomechanical tests were repeated by which the same data collected at the baseline session were recollected again.

6.3.5 Study intervention program.

The participants were instructed to wear the AposTherapy system during walking while performing their daily activities for period of a minimum of 60 minutes. The duration of the intervention was for six weeks.

6.3.6 The Knee Osteoarthritis Outcome Score (KOOS).

The challenge in the rehabilitation of players after ACLR is to determine the safe time to return to demanding athletic activities (Salavati et al., 2011). Therefore, clinicians tend to utilise patients-oriented outcome measures to establish the success of ACLR and rehabilitation (Shaw et al., 2004). The KOOS (knee injury osteoarthritis outcome score) questionnaire, an extension of the WOMAC (Western Ontario and McMaster Universities Osteoarthritis Index), helps to determine the quality of life and functional status of active patients with knee injury who are at high risk to develop premature osteoarthritis (Bekkersy et al., 2009; Salavati et al., 2011).

The use of a self-reported outcome measure is recommended as part of a series of measurements to determine functional status following ACL injury, and it also determines the readiness to return to sporting activities following ACLR (Bekkersy et al., 2009; Salavati et al., 2011). This is a self-administered questionnaire that help to evaluate knee-related issues. It contains 42 items in five separate subscales: pain (9 items), symptoms and stiffness (7 items), activity of daily living (9 items), activity of daily living (17 items), functioning sport and recreation activities (5 items), and knee-related quality of life (4 items) (Roos et al., 2003). The self-reported outcome is a subjective measure, demonstrating the patient's perception of function, symptoms, sport-related disability, and pain (Roos et al., 2003). The participants in the study responded to the KOOS questionnaire at the initial and final sessions, to allow different pain, activity daily living (ADL) symptoms, quality of life (QOL), sport and recreational scores to be collected to determine any alteration in these measures.

6.4 Data processing.

All of the data were processed in the same manner as the feasibility study whereby kinematic, kinetic EMG and CoP-Excursion data processing methods previously descripted in section 3.3.4 of Chapter Three were used.

6.5 Data analysis.

The sample size of five participants was considered low to judge normal distribution (Ghasemi and Zahediasl, 2012). Thereby, Wilcoxon signed rank test was utilized. The entire statistical analysis was performed in SPSS (Version 24.0. IBM SPSS Statistics, USA). Effect size(d) was calculated to indicated the magnitude of changes in the dependent variable assessment to determine the degree of effect of the intervention. The Cohen's d values were used to calculated ($d = \frac{Xi-Xv}{\mathrm{SDc}}$), the effect size of each of the study intervention groups by using the SPSS and web site http://www.uccs.edu/faculty/backer/. A strong effect size was defined by d >0.8, moderate between 0.8 and 0.2, and low ≤0.2 (Cohen et al., 1988).

6.6 Results.

The main changes were seen in the participants, which exhibited major improvements in their frontal plane motion on the knee joint levels in particularly their knee valgus motion while performing SLL and SLS tasks (Table 6-1 and Table 6-5, respectively). Furthermore, knee valgus moments showed a non-significant reduction during SLL and SLS tasks. Interestingly, the knee valgus motion and momens values drop at post-test to levels exceeding the MDD values previously reported (Chapter Three in section 3.2.7.2). In addition, participants showed significant improvement in postural stability measures (Table 6-26). In regarding the KOOS subscales there was significant change in KOOS quality of life (QOL) subscale in comparison to its baseline values Table 6-27. When looking at the changes seen at muscular recruitment pattern at quadriceps and hamstring. There were no significant changes observed in the muscle co-contraction in feedforward (100 milliseconds prior to initial contact), feedback (100 milliseconds after initial contact) motor control phases and between the medical and lateral co-contraction ration.

6.6.1 Kinematic results of the contralateral leg during single leg landing (SLL).

6.6.1.1 Maximum knee valgus angle.

After using the AposTherapy system there was a significant decrease, in the maximum knee valgus angle in comparison to their baseline values. There was a significant large (d=1.73) decrease in the maximum knee valgus angle. Descriptive data of the knee valgus angle results during SLL task are illustrated in Figure 6-1 and Table 6-1.

Table 6-2 : The mean, standard deviation (SD) and the mean difference (Mean diff.) of the knee valgus angle of pre-and post-test for SLL task.

Task	**Knee Valgus Angle**				
SLL	Mean (°)	SD (°)	p	MDD	Effect size
Pre-test	-5.53	3.63	0.04		1.73
Post-test	1.87	4.79			
Mean diff	7.4	3.6		2.30	

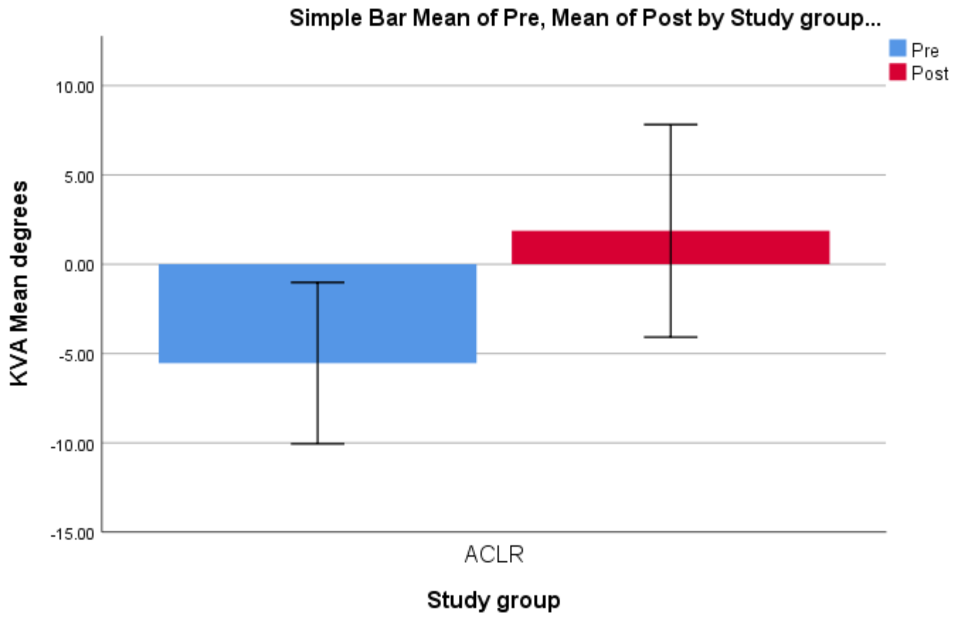


Figure 6- 1: The mean and standard deviation (SD) and the mean difference (Mean diff) of the knee valgus angle (KVA) of pre-and post-test for SLL task. Y –axis KVA (degrees) and X-axis pre-post test.

6.6.1.2 Maximum knee flexion angle.

After using the AposTherapy system for six weeks, there was no significant change in the maximum knee flexion angle in comparison to their baseline values. Descriptive data of knee flexion angle results during SLL task are illustrated in Table 6-2.

Table 6- 3: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the knee flexion angle of pre-and post-test for SLL task.

Task		**Knee Flexion Angle**		
SLL	Mean (°)	SD (°)	MDD	P
Pre-test	67.77	5.65		0.68
Post-test	71.24	7.94		
Mean diff	3.43	7.02	3.13	

6.6.1.3 Maximum hip adduction angle.

After using the AposTherapy system there was no significant change in the maximum hip adduction angle in comparison to their baseline values. Descriptive data of hip adduction angle results during SLL task are illustrated in Table 6-3.

Table 6- 4: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the hip adduction angle of pre-and post-test for SLL task.

Task		**Hip Adduction Angle**		
SLL	Mean (°)	SD (°)	MDD	P
Pre-test	8.39	6.8		0.23
Post-test	3.43	4.66		
Mean diff	4.95	4.28	6.12	

6.6.1.4 Maximum ankle dorsiflexion angle.

After using the AposTherapy system there was no significant change in the maximum dorsiflexion angle in comparison to their baseline values. Descriptive data of dorsiflexion angle results during SLL task are illustrated in Table 6-4.

Table 6- 5: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the ankle dorsiflexion angle of pre-and post-test for SLL task.

Task		**Ankle Dorsiflexion Angle**		
SLL	Mean (°)	SD (°)	MDD	p
Pre-test	29.12	4.44		0.04
Post-test	26.55	5.12		
Mean diff	2.57	2.21	3.75	

6.6.2 Kinematic results of the contralateral leg during single leg squat (SLS).

6.6.2.1 Maximum knee valgus angle.

After using the AposTherapy system there was no significant difference in the maximum knee valgus angle in comparison to their baseline values. There was a significant large (d=0.88) decrease in the maximum knee valgus angle Descriptive data of knee valgus angle results during SLS task are illustrated in Figure 6-2 and (able 6-5.

Table 6- 6: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the knee valgus angle of pre-and post-test for SLS task.

Task			Knee Valgus Angle		
SLS	Mean (°)	SD (°)	p	MDD	Effect size
Pre-test	-4.67	5.48	0.04		0.88
Post-test	-0.61	3.47			
Mean diff	4.05	3.61		2.53	

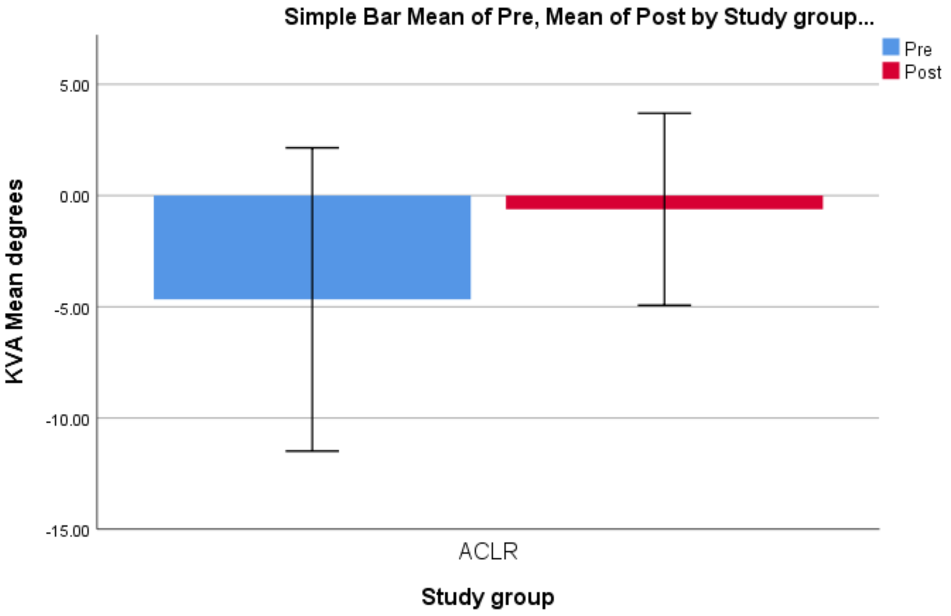


Figure 6- 2:The mean and standard deviation (SD) and the mean difference (Mean diff) of the knee valgus (KVA) angle of pre-and post-test for SLS task. Y –axis KVA (degrees) and X-axis pre-post test.

6.6.2.2 Maximum knee flexion angle.

After using the ApոsTherapy system there was no significant change in the maximum knee flexion angle in comparison to their baseline values. Descriptive data of knee flexion angle results during SLS task are illustrated in Table 6-6.

Table 6- 7: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the knee flexion angle of pre-and post-test for SLS task.

Task	**Knee Flexion Angle**			
SLS	Mean (°)	SD (°)	MDD	P
Pre-test	74.99	11.02		0.50
Post-test	72.52	11.6		
Mean diff	2.47	8.15	4.73	

6.6.2.3 Maximum hip adduction angle.

After using the AposTherapy system there was no significant change in the maximum hip adduction angle in comparison to their baseline values. Descriptive data of hip adduction angle results during SLS task are illustrated in Table 6-7.

Table 6- 8: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the hip adduction angle of pre-and post-test for SLS task.

Task		**Hip Adduction Angle**		
SLS	Mean (°)	SD (°)	MDD	P
Pre-test	10.69	7.53		0.50
Post-test	6.81	3.68		
Mean diff	3.87	6.71	6.21	

6.6.2.4 Maximum ankle dorsiflexion angle.

After using the AposTherapy system there was no significant change in the maximum dorsiflexion angle in comparison to their baseline values. Descriptive data of dorsiflexion angle results during SLS task are illustrated in Table 6-8

Table 6- 9: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the ankle dorsiflexion angle of pre-and post-test for SLS task.

Task		**Ankle Dorsiflexion Angle**		
SLS	Mean (°)	SD (°)	MDD	p
Pre-test	34.43	4.03		0.05
Post-test	30.97	7.41		
Mean diff	3.45	3.52	3.67	

6.6.3 Kinetic results of the contralateral leg during single leg landing (SLL).

6.6.3.1 Maximum external knee valgus moment.

After using the AposTherapy system there was no significant change in the maximum knee valgus moment in comparison to their baseline values. Descriptive data of knee valgus moment results during SLL task are illustrated in Figure 6-3 and Table 6-9.

Table 6-10: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the knee valgus moment of pre-and post-test for SLL task.

Task		**Knee Valgus Moment**		
SLL	Mean (Nm/Kg)	SD (Nm/kg)	MDD	P
Pre-test	0.35	0.28		0.43
Post-test	0.14	0.07		
Mean diff	0.21	0.31	0.14	

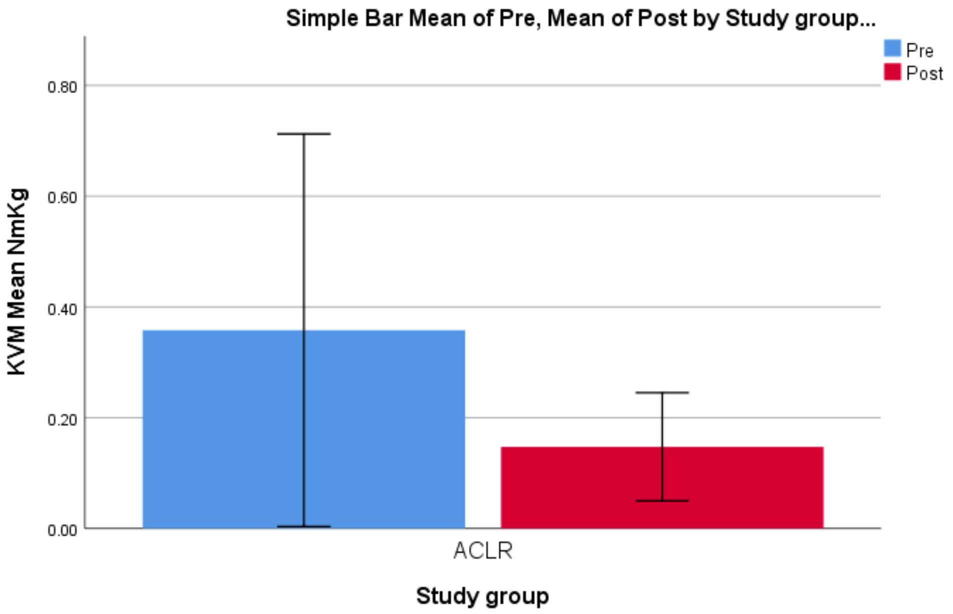


Figure 6- 3:The mean and standard deviation (SD) and the mean difference (Mean diff) of the knee valgus moment (KVM) of pre-and post-test for SLL task. Y –axis KVM (Nm/kg) and X-axis pre-post test.

6.6.3.2 Maximum external knee flexion moment.

After using the AposTherapy system there was no significant change in the maximum knee flexion moment in comparison to their baseline values. Descriptive data of knee flexion moment results during SLL task are illustrated in Table 6-10.

Table 6- 11: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the knee valgus moment of pre-and post-test for SLL task.

Task		Knee Flexion Moment		
SLL	Mean (Nm/kg)	SD (Nm/kg)	MDD	P
Pre-test	2.34	0.75		0.68
Post-test	2.48	0.55		
Mean diff	0.14	0.41	0.41	

6.6.3.3 Maximum external hip adduction moment.

After using the AposTherapy system there was no significant change in the maximum hip adduction moment in comparison to their baseline values. Descriptive data of hip adduction moment results during SLL task are illustrated in Table 6-11.

Table 6-12: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the hip adduction moment of pre-and post-test for SLL task.

Task		Hip Adduction Moment		
SLL	Mean (Nm/kg)	SD (Nm/kg)	MDD	P
Pre-test	1.55	0.79		0.72
Post-test	1.37	0.07		
Mean diff	0.17	0.74	0.27	

6.6.3.4 Maximum vertical ground reaction force (GRF).

After using the AposTherapy system there was no significant change in the maximum vertical ground reaction force in comparison to their baseline values. Descriptive data of the vertical ground reaction force results during SLL task are illustrated in Table 6-12.

Table 6-13: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the GRF of pre- and post-test for SLL task.

Task		**GRF for SLL**		
SLL	Mean (*BW)	SD(*BW)	MDD	P
Pre-test	2.63	0.39		0.89
Post-test	2.53	0.34		
Mean diff	0.09	0.57	0.46	

6.6.4 Kinetic results of the contralateral leg during single leg squat (SLS).

6.6.4.1 Maximum external knee valgus moment.

After using the AposTherapy system there was no significant change in the maximum knee valgus moment in comparison to their baseline values. Descriptive data of knee abduction moment results during SLS task are illustrated in Figure 6-4 and Table 6-13.

Table 6-14: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the knee valgus moment of pre-and post-test for SLS task.

Task		**Knee Valgus Moment**		
SLS	Mean (Nm/kg)	SD (Nm/kg)	MDD	P
Pre-test	0.31	0.37		0.08
Post-test	0.03	0.02		
Mean diff	0.28	0.39	0.05	

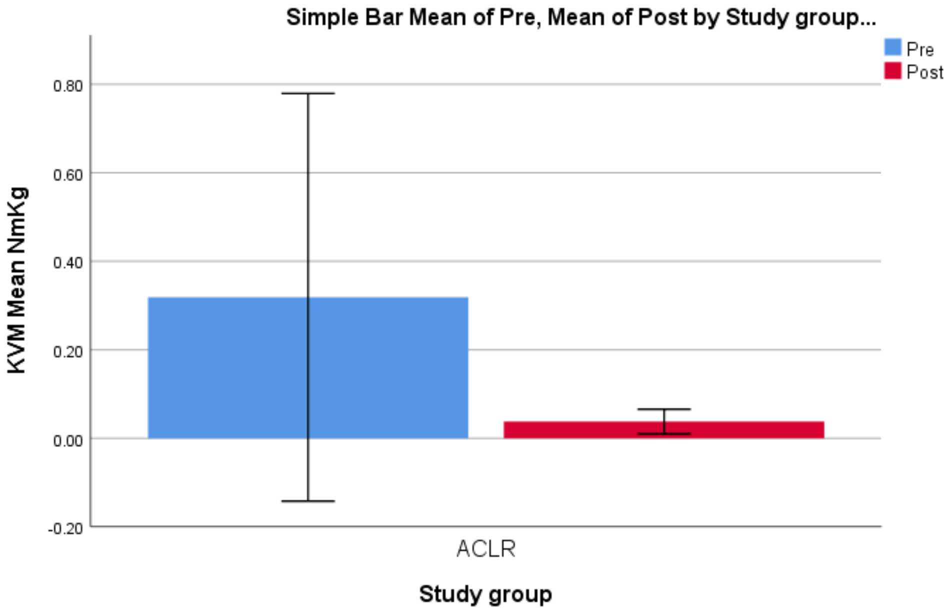


Figure 6- 4: The mean and standard deviation (SD) and the mean difference (Mean diff) of the knee valgus moment (KVM) of pre-and post-test for SLS task. Y –axis KVM (Nm/kg) and X-axis pre-post test.

6.6.4.2 Maximum external knee flexion moment.

After using the AposTherapy system there was no significant change in the maximum knee flexion moment in comparison to their baseline values. Descriptive data of knee flexion moment results during SLS task are illustrated in Table 6-14.

Table 6-15: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the knee flexion moment of pre-and post-test for SLS task.

Task		**Knee Flexion Moment**		
SLS	Mean (Nm/kg)	SD (Nm/kg)	MDD	P
Pre-test	1.73	0.22		0.23
Post-test	1.56	0.44		
Mean diff	0.17	0.28	0.16	

6.6.4.3 Maximum external hip adduction moment.

After using the AposTherapy system there was no significant change in the maximum hip adduction moment in comparison to their baseline values. Descriptive data of hip adduction moment results during SLS task are illustrated in Table 6-15.

Table 6-16: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the hip adduction moment of pre-and post-test for SLS task.

Task		**Hip Adduction Moment**		
SLS	Mean (Nm/kg)	SD (Nm/kg)	MDD	P
Pre-test	0.99	0.45		0.23
Post-test	0.76	0.08		
Mean diff	0.23	0.08	0.19	

6.6.4.4 Maximum vertical ground reaction force (GRF).

After using the AposTherapy biomechanical device there was no significant change in the maximum vertical ground reaction force in comparison to their baseline values. Descriptive data of GRF results during SLS task are illustrated in Table 6-16.

Table 6-17: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the GRF of pre- and post-test for SLL task.

Task		GRF for SLS		
SLS	Mean(*BW)	SD (*BW)	MDD	P
Pre-test	1.14	0.07		0.68
Post-test	1.11	0.03		
Mean diff	0.03	0.09	0.05	

6.6.5 Electromyography results of the contralateral leg during single leg landing task (SLL).

When looking between the pre-post assessments for the study participants, there were no significant difference in any of the measures regarding muscular activity.

6.9.5.1 Medial side knee muscle Vastus Medialis and Semitendinosus (VM-ST) co-contraction index during feed-forward motor control phase (100 ms prior to initial contact) during SLL task.

After using the AposTherapy system there was no significant difference in the maximum Vastus Medialis and Semitendinosus (VM-ST) co-contraction index at feed-forward motor control phase (100 ms prior to initial contact) during SLL task in comparison to their baseline values. Descriptive data of results Vastus Medial and Semitendinosus (VM-ST) co-contraction index at feed-forward motor control phase (100 ms prior to initial contact), during SLL task are illustrated in Table 6-17.

Table 6-18: The mean, standard deviation (SD) and the mean difference (Mean diff.) of % MVIC for (VM-ST) co-contraction index at feed-forward motor control phase during SLL task.

Task		**VM-ST CCI Feed-forward**		
SLL	Mean(%MVIC)	SD(%MVIC)	MDD	P
Pre-test	32.82	19.84		0.17
Post-test	46.61	32.60		
Mean diff	13.81	15.54	9.95	

Single legged landing (SLL), Medial knee muscles Vastus Medialis –Semitendinosus (VM-ST), and Co-contraction index (CCI).

6.6.5.1 Medial side knee muscle Vastus Medialis and Semitendinosus (VM-ST) co-contraction index during feed-back motor control phase (100 ms prior to initial contact) during SLL task.

After using the AposTherapy system there was no significant change in the maximum Vastus Medialis and Semitendinosus (VM-ST) co-contraction index at feed-back motor control phase (100ms after to initial contact) during SLL task in comparison to their baseline values. Descriptive data of results Vastus Medial and Semitendinosus (VM-ST) co-contraction index at feed-back motor control phase (100ms after to initial contact), during SLL task are illustrated in Table 6-18.

Table 6-19: The mean, standard deviation (SD) and the mean difference (Mean diff.) of % MVIC for (VM-ST) co-contraction index at feed-back motor control phase during SLL task.

Task		VM-ST CCI Feed-back		
SLL	Mean(%MVIC)	SD(%MVIC)	MDD	P
Pre-test	59.85	31.77		0.08
Post-test	52.22	25.48		
Mean diff	7.63	7.49	15.3	

Single legged landing (SLL), Medial knee muscles Vastus Medialis –Semitendinosus (VM-ST), and Co-contraction index (CCI).

6.6.5.2 Lateral side knee muscle Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index during feed-forward motor control phase (100ms prior to initial contact) during SLL task.

After using the AposTherapy system there was no significant difference change in the maximum Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index at feed-forward motor control phase (100ms prior to initial contact) during SLL task in comparison to their baseline values. Descriptive data of results Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index at feed-forward motor control phase (100ms prior to initial contact), during SLL task are illustrated in Table 6-19.

Table 6-20: The mean, standard deviation (SD) and the mean difference (Mean diff.) of %MVIC for (VL-BF) co-contraction index at feed-forward motor control phase during SLL task.

Task	**VL-BF CCI Feed-forward**		
SLL	Mean(%MVIC)	SD(%MVIC)	P
Pre-test	23.82	12.45	0.28
Post-test	40.62	31.84	
Mean diff	16.80	30.11	

Single legged landing (SLL), Lateral knee muscles Vastus Lateralis –Biceps Femoris (VL-BF), and Co-contraction index (CCI).

6.6.5.3 Lateral side knee muscle Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index during feed-back motor control phase (100 ms after to initial contact) during SLL task.

After using the AposTherapy system there was no significant difference change in the maximum Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index at feed-back motor control phase (100ms after to initial contact) during SLL task in comparison to their baseline values. Descriptive data of results Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index at feed-back motor control phase (100ms prior to initial contact), during SLL task are illustrated in Table 6-20.

Table 6-21: The mean, standard deviation (SD) and the mean difference (Mean diff.) of % MVIC for (VL-BF) co-contraction index at feed-back motor control phase during SLL task.

Task	**VL-BF CCI Feed-back**			
SLL	Mean(%MVIC)	SD(%MVIC)	MDD	P
Pre-test	27.63	16.10		0.13
Post-test	54.01	40.26		
Mean diff	27.62	32.44	11.91	

Single legged landing (SLL), Lateral knee muscles Vastus Lateralis –Biceps Femoris (VL-BF), and Co-contraction index (CCI).

6.6.5.4 Medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-forward phase motor control (100ms prior to initial contact) during SLL task.

After using the AposTherapy system there was no significant difference change. In the medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-forward motor control phase (100ms prior to initial contact) during SLL task in comparison to their baseline values. Descriptive data of results in the medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-forward motor control phase (100ms prior to initial contact) during SLL task are illustrated in Table 6-21.

Table 6-22: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-forward motor control phase during SLL task.

Task	Mad (VM-ST)/Lat (VL-BF) CCI ratio Feed-forward			
SLL	Mean	SD	MDD	P
Pre-test	1.33	0.15		0.60
Post-test	1.65	1.38		
Mean diff	0.32	1.37	0.28	

Single legged landing (SLL), Medial knee muscles Vastus Medialis –Semitendinosus (VM-ST) to lateral knee muscles Vastus Lateralis –Biceps Femoris (VL-BF), and Co-contraction index (CCI).

6.6.5.5 Medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-back motor control phase (100ms after to initial contact) during SLL task.

After using the AposTherapy system there was no significant difference change in the medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-back motor control phase (100ms after to initial contact) during SLL task in comparison to their baseline values. Descriptive data of results in the medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-back motor control phase (100ms after to initial contact) during SLL task are illustrated in Table 6-22.

Table 6-23: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the medial (VM-ST) to lateral (VL-BF) co-contraction index ration at the feed-back motor control phase during SLL task.

Task	**Med (VM-ST)/Lat (VL-BF) CCI ratio Feedback**			
SLL	Mean	SD	MDD	P
Pre-test	2.21	0.84		0.10
Post-test	1.16	0.66		
Mean diff	1.05	1.13	0.46	

Single legged landing (SLL), Medial knee muscles Vastus Medialis –Semitendinosus (VM-ST) to lateral knee muscles Vastus Lateralis –Biceps Femoris (VL-BF), and Co-contraction index (CCI).

6.6.6 Electromyography results of the of the Contralateral leg during single leg squat task (SLS).

6.6.6.1 Medial side knee muscle Vastus Medialis and Semitendinosus (VM-ST) co-contraction index during SLS task.

After using the AposTherapy system there was no significant difference change in the maximum Vastus Medial and Semitendinosus (VM-ST) co-contraction index during SLS task in comparison to their baseline values. Descriptive data of results Vastus Medial and Semitendinosus (VM-ST) co-contraction index during SLS task are illustrated in Table 6-23.

Table 6-24: The mean, standard deviation (SD) and the mean difference (Mean diff.) of (VM-ST) co-contraction index during SLS task.

Task	**VM-ST CCI**			
SLS	Mean(%MVIC)	SD(%MVIC)	MDD	P
Pre-test	32.26	12.5		0.55
Post-test	37.42	18.14		
Mean diff	5.24	17.94	12.95	

Single leg squat (SLS), Medial knee muscle Vastus Medialis and Semitendinosus (VM-ST), and Co-contraction index (CCI).

6.6.6.2 Lateral side knee muscle Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index) during SLS task.

After using the AposTherapy system there was no significant difference change in the maximum Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index during SLS task in comparison to their baseline values. Descriptive data of results Vastus Lateralis and Biceps Femoris (VL-BF) co-contraction index during SLS task are illustrated in Table 6-24.

Table 6-25: The mean, standard deviation (SD) and the mean difference (Mean diff.) of (VL-BF) co-contraction index during SLS task.

Task	**VL-BF CCI**			
SLS	Mean(%MVIC)	SD(%MVIC)	MDD	P
Pre-test	21.48	11.72		0.31
Post-test	27.42	22.42		
Mean diff	6.06	11.30	11.14	

Single leg squat (SLS), Lateral knee muscles Vastus Lateralis and Biceps Femoris (VL-BF) and Co-contraction index (CCI).

6.6.6.3 Medial (VM-ST) to lateral (VL-BF) co-contraction index ration during SLS task.

After using the AposTherapy system there was no significant difference change in the medial (VM-ST) to lateral (VL-BF) co-contraction index during SLS task in comparison to their baseline values. Descriptive data of results in the medial (VM-ST) to lateral (VL-BF) co-contraction index ration during SLS task are illustrated in Table 6-25.

Table 6-26: The mean, standard deviation (SD) and the mean difference (Mean diff.) of the medial (VM-ST) to lateral (VL-BF) co-contraction index ration during SLS task.

Task	**Med (VM-ST) /Lat (VL-BF) CCI ratio**			
SLS	Mean	SD	MDD	P
Pre-test	1.86	1.28		0.51
Post-test	2.08	2.02		
Mean diff	0.28	0.96	.029	

Single leg squat (SLS), Standard deviation(SD), Medial knee muscles the Vastus Medialis – Semitendinosus (VM-ST), Lateral knee muscles the Vastus Lateralis -Biceps Femoris (VL-BF) and Co-contraction index (CCI).

6.6.7 Centre of Pressure Excursion (CoP-Excursion).

After using the AposTherapy system there was significant in the range of motion for the cop-excursion in comparison to the baseline values. There was a significant large (d=1.04) reduction in the CoP-Excursion. Descriptive data of results in CoP-Excursion are illustrated in Figure 6-5 and Table 6-26.

Table 6-27: The mean, standard deviation (SD) and the mean difference (Mean diff.) of CoP-Excursion during Single Leg Stance task.

Task			**CoP-Excursion**		
Single-Leg Stance	**Mean(mm)**	**SD(mm)**	**MDD**	**p**	**Effect size**
Pre-test	41.18	29.65		0.04	1.04
Post-test	18.80	7.25			
Mean diff	23.0	22.64	11.2		

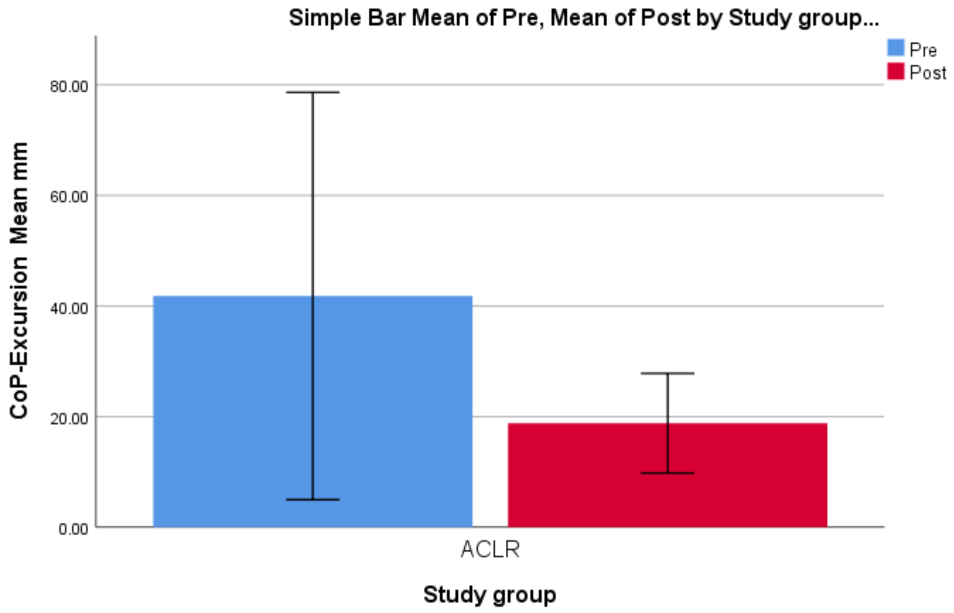


Figure 6- 5:The mean and standard deviation (SD) and the mean difference (Mean diff) of the CoP-Excursion of pre- and post-test for Single-leg Stance. Y –axis Cop Excursion (mm) and X-axis Sudy groups.

6.6.8 Knee Injury and Osteoarthritis Outcome Score (KOOS).

After using the AposTherapy system there was no significant change in KOOS pain, symptoms, ADL, sport and recreation activity, respectively, in comparison to its baseline values. However, after using the the AposTherapy system, there was significant change in KOOS quality of life (QOL) subscale in comparison to its baseline values. Descriptive data of results in the KOOS subscales are illustrated in Table 6-27.

Table 6-28: The mean, standard deviation (SD) and the mean difference (Mean diff.) of for the KOOS pain subscale.

Variables	Pre-test	Post-test	Mean diff	p	Effect size
KOOS Pain	85.0±6.1	91.4±7.7	6.40±5.10	0.06	
KOOS Sport & recreation activity	75.4±19.5	80.4±18.7	5.0±3.53	0.06	
KOOS Symptoms	83.8±10.3	93.5±9.6	3.8±4.54	0.11	
KOOS ADL	93.0±7.6	97.6±3.7	1.4±1.94	0.18	
KOOS QOL	66.2±10.4	80.4±8.7	14.2±6.61	0.04	1.48

6.7 Discussion.

The aim of this study was to understand whether employing the AposTherapy system would alter risk factors associated with a second ACL injury in contralateral limb. This study, investigate the effect of implementing AposTherapy intervention on individuals who had reconstruction operation after using the AposTherapy system. All participants demonstrated poor neuromuscular control at their contralateral knee prior to the study intervention. The discussion will follow by assessing each hypothesis in turn.

6.7.1 Postural stability.

- Hypothesis 1: There is no significant difference in postural stability that is reflected by the centre of pressure measures (CoP-excursion) before and after the AposTherapy intervention during single leg stance task.

The results obtained in this study are in agreement with main study (Chapter Five) in terms of achieving significant improvements in postural stability measures. There was a demonstrated significant reduction in CoP-excursion with an average reduction by 46.8% on average when compared with their baseline values. This does demonstrate that the intervention appears highly effective. Nonetheless, the effects size of the participants for CoP excursion was (d= 1.04), which would be considered to be larger (d >0.8) according to Cohen et al. (1988) and clinically significantly. However, the percentage improvement was lower than the walking group in the main study which was (75.5%). This result is likely due to the small sample size of the present study.

Several mechanisms have been postulated to account for a bilateral deficit in postural stability as a consequence of ACL rupture. The pre-existent bilateral deficit in postural stability may be because the impairment in knee proprioception, which may have predisposed the primary ACL injury at the first place. (Zouita et al., 2009; Negahban et al., 2014; Heinert et al., 2018). Poterno et al. (2010), found deficits in postural stability were predictive of a second ACL injury in surgical reconstructed patients. Similarly, Mohammadi et al. (2012), investigated the relationship between static and dynamic postural stability in athletes for an average of eight months after ACLR and reported difference in the ACLR operated limb compared to the uninjured limb and compared to healthy control for all parameters of postural stability including anterior and posterior, medial and lateral amplitude and velocity (Mohammadi et al., 2012). Changes in knee proprioception after ACL injury and post-ACLR have been widely reported within the literature (Reider et al., 2003; Paterno et al., 2010; Mohammadi et al., 2012; Relph et al., 2016; Heinert et al., 2018).

The ACL mechanoreceptors are thought to provide direct afferent information to the spinal cord and supraspinal area regarding joint position (Mohammadi et al., 2012). Schuttle et al. (1987), reported the neurologic composition of the ACL include neural connections from the ACL to the spinal cord and supraspinal areas, following reconstruction of the ligament, restoration of the sensor function may not fully recovery. Young et al. (2016), reported no evidence of mechanoreceptor re-innervation in reconstructed ACL an average of 6.9 years post-ACLR. This lack of sensory input may influence dynamic postural stability and movement strategies in the ACLR athletes.

Loss of afferent information due to ACL rupture may affect not only the joint stabilisation and neuromuscular function of the ipsilateral ACL injured knee but also the contralateral uninjured knee (Ageberg et al., 2004). Furthermore, When ACL is ruptured that may diminish sensory information from the ipsilateral side, which would put a challenge on the neuromuscular system to efficiently control both lower limbs with different sensory properties (Bonfim et al., 2008). Thus, the motor control system would rather reduce the performance of the contralateral limb in addition to the ipsilateral knee. This may result in adjustments of motor coordination (Bonfim et al., 2008). The deficit in the afferent information from the ruptured ACL has been postulated to even affect contralateral knee neuromuscular function (Lysholm et al., 1998). Nevertheless, larger postural sway in the contralateral limb was observed in compared with and matched healthy controls (Okuda et al., 2005; Negahban et al., 2009). In a systematic review study by Negahban et al. (2014) no significant differences were observed between the ipsilateral and contralateral legs in regard to postural stability deficit with patients who previously sustained ACL rupture (Negahban et al., 2014).

The late phases of post-ACLR rehabilitation programs would ideally target neuromuscular deficits presented with an aim to address residual pre-injury and post-injury movement deficits (Hewett et al., 2013; Paterno et al., 2010). Therefore, the long-term benefits of an effective post-ACLR rehabilitation programs may also be realised, both by the full restoration of functional performance, and by the improved ability of these individuals to maintain lifetime activity participation without enduring second ACL injury (DiStasi et al., 2013). The likelihood of deficit in postural stability in both lower limbs following ACL injury would highlight limitations in some of the exiting rehabilitation programs and return to functional activity criteria (DiStasi et al., 2013). The use of the contralateral limb as bench mark for ipsilateral injured side may lead to misinterpretation of the real ability of patient to safely return to high demand functional activities such as sports (Eitzen et al., 2010; Negahban et al., 2014). Therefore, it is important to ensure that both limbs during post-ACLR received adequate rehabilitation to improve the postural stability before to allow return to functional activates which may be were a device such as the AposTherapy system may be required in the late stage of post-ACLR rehabilitation prior to return to sport activities.

In summary, there was a significant reduction in CoP-excursion variables reflecting improvements in postural degree of stability. Nonetheless, as poor postural stability has been documented as one of the risk factors of second ACL injury, this result is considerably promising. Therefore, the null hypothesis was rejected as postural stability was significantly improved in the sample population.

6.7.2 Kinematic and kinetic outcomes.

- Hypothesis 2: There is no significant difference in maximum knee valgus angle, before and after the AposTherapy intervention during single leg squatetask (SLS) and single leg landing task (SLL).

- Hypothesis 3: There is no significant difference in maximum knee valgus moments before and after the AposTherapy intervention during single leg squat task (SLS) and single leg landing task (SLL).

The residual neuromuscular and biomechanical deficits are highly predicative of a second ACL injury after the athletes with primary ACLR resume athletic participation (Lustosa et al., 2011; Paterno et al., 2010). Interestingly, knee valgus motion and moments appear to be a key factor in both primary (Hewett et al., 2005) and second ACL injury risk models (Paterno et al., 2010). Although the efficacy of NMT in decreasing the risk of second ACL injury has not been empirically tested, the demonstrated reduction of primary injury incidence using similar methods has proven effective (DiStasi et al., 2013; Myer et al., 2013; Sugimoto et al., 2012). Thereby, applying targeted NMT may have the greatest effect on the modification of the neuromuscular component of second ACL injuries (DiStasi et al., 2013).

The results showed that the knee valgus angle had a significant reduction during the single-leg landing (SLL) task. The mean difference was 7.4 ± 3.6° which may be considered clinically significant as it far exceeded the MDD values of 2.30° for knee valgus angles during SLL task reported in the reliability study (Chapter Three in section 3.2.7.2). In addition, showed effect size of (d= 1.73), which would be considered largely effective (d >0.8) according to Cohen et al. (1988). This was a greater reduction than what was observed in Chapter Five in the walking group during the SLL task (Mean diff ±SD: 3.42 ± 3.71°). Furthermore, knee valgus angle had a significant reduction during the SLS task. The mean difference was 4.0 ± 3.6° which may be considered clinically significant as it exceeded the MDD values of 2.5° for knee valgus angle during SLS task reported in the reliability study (Chapter Three in section 3.2.7.2). In addition, knee valgus angle during SLS task showed effect size of d=0.88, which is considered large effect size. However, it was less than the effect size observed during SLL task. Additionally, the external knee valgus moment during the SLL task (Table 6-9) and SLS tasks (Table 6-14) did not show significant changes but did reduce in magnitude when compared with their baseline values. Interestingly, the knee valgus moment values during SLL and SLS tasks drop at post-test to levels exceeding MDD values previously reported in reliability study (Chapter Three in section 3.2.7.2). This may be due to low sample size and high variability in the sample population, which could be the reason for the lack of significance. Interestingly, the degree of reduction was greater when compared with the walking intervention group knee valgus angle and moments in the main study in Chapter Five. This might be due to the nature of the sample population who had post-ACLR and would have higher potential for second ACL injury in their contralateral knee with the persistent deficit in biomechanical and neuromuscular risk factor. Thus, may reflect in greater response to study intervention (Myer et al., 2007, Lim et al., 2009). This observed changes in knee valgus angles would have a considerable importance as excessive knee valgus loading specifically was not identified as a predictive component of the second ACL injury risk model (Paterno et al., 2010). While high knee valgus angle was considered a significant predictive variable and is an important component in the calculation of external knee valgus loads (Paterno et al., 2010).

In regarding hip adduction angle and moments during the SLL task did not show significant changes. This was similar to results shown by the walking group in the main study Chapter Five, where significant changes were also not evident. However, there was a lower reduction in the hip adduction angle during the SLL task, when compared with their baseline values. Meanwhile, the hip adduction angle during the SLS task also showed a non-significant reduction but did not meet statistical significance. When comparing the changes between the results found in Chapter Five and these results, it appears that the changes were superior than the ones shown in walking group previously. This may be due to the nature of the sample population who had post-ACLR and would have higher potential for second ACL in their contralateral knee with the persistent deficit in biomechanical and neuromuscular risk factor. Thus, may reflect in greater response to study intervention.

When considering other secondary outcomes, there was a small difference in the sagittal plane variables. The knee flexion angle and motion showed minor changes; there was a slight increase in the knee flexion angle and moment values during the SLL and SLS tasks, except in knee flexion angle during SLS task that showed a slight decrease by 0.66% on average in comparison with the baseline values. A systemic review compared the knee biomechanics during walking of ACLR knee and healthy control individuals, the authors identified reduction in peak flexion motion and moments to be identified within the first year post-ACLR (Hart et al., 2016). In addition, there was a reduction in GRF during SLL and SLS study tasks on average of 2.97% and 2.63%, respectively, in comparison to their baseline values. This may be a promising observation as high GRF in considered one of the risk factors for many musculoskeletal injuries of lower limbs particularly the ACL (Bates et al., 2015; Zahradnik et al., 2015). However, the changes in GRF were not significant.

Moreover, the outcomes demonstrated in the current study may be attributed to the perturbation training element with the adjusted knee alignment that the AposTherapy system delivered. Previous studies have demonstrated the abilities of the AposTherapy system that allow various modes of biomechanical manipulation. Control manipulation of the device element can alter the foot CoP location (Khoury et al., 2013, 2015), affecting the kinematic and kinetic parameters of gait for both osteoarthritis patients and healthy individuals (Khoury et al., 2015; Haim et al., 2011, 2012). The convex design of the AposTherapy system offers slight instability when worn. Thereby, challenging the dynamic stability of the knee joint when in the desired alignment position. Hence, when the subjects wear the device while walking, this may induce dynamic perturbation (Khoury et al., 2013).

This observation may be evident as patients who previously sustained NCACL injury, and had reconstruction surgery showed a higher risk of sustaining a second ACL injury (either graft failure or contralateral injury) compared to individuals who did not sustain a primary ACL injury (Paterno, et al., 2012, 2015; Wiggins, et al., 2016). Residual functional impairments implicated for the primary ACL injury may continue to exceed even after restoring mechanical stability by undergo ACLR and rehabilitation program (Eitzen et al., 2009; Roewer et al., 2011; DiStasi et al., 2013; Gokeler et al., 2013; Xergia et al., 2015; DiStasi et al., 2015; Hart et al., 2016; Nagelli et al., 2017). Thereby, it may display a better adaptation to NMT in terms of reducing the risk for second ACL injury (Lim, et al., 2009; Myer, et al., 2007).

In summary, the knee valgus angle significantly decreased during the SLL and SLS tasks. The knee valgus moment showed trend toward reduction; however, it did not reach statistical significance levels. The small sample size may affect this outcome, and in a larger population sample, significant levels may have been evident. Therefore, the second null hypothesis was rejected regarding the use of AposTherapy system which showed significantly reduction knee valgus motion during SLL and SLS tasks. On the contrary, the third nul hypothesis was accepted because there was no significant change in knee valgus moment in both tasks.

6.7.3 Muscular co-contraction.

- Hypothesis 4: There is no significant difference in muscle co-contraction of the medial side of the knee (Vastus Medialis and Semitendinosus), before and after the AposTherapy intervention during Single leg squat task (SLS) and Single leg landing task (SLL).

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- Hypothesis 5: There is no significant difference in muscle co-contraction of the lateral side of the knee (Vastus Lateralis and Biceps Femoris), before and after the AposTherapy intervention during Single leg squat task (SLS) and Single leg landing task (SLL).

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The co-contraction of the muscles around the knee joint at a sufficient pattern would compress the joint enough to withstand valgus load by articular contract forces, and this may protect the ACL from high loads (Hewett et al., 2005). The co-contraction of the quadriceps and hamstring not only protects the knee joint against excessive anterior drawer, but also helps it withstand excessive dynamic lower limb valgus (Hewett et al., 2005; Besier et al., 2003). The coordinated of the hamstring and quadriceps activation may play a role in mitigating primary injury risk by way of reducing ACL strain and promoting normal landing mechanics (Ford et al., 2011). Balanced against and antagonist recruitment may also protect the reconstructed knee against second ACL injury via similar protective mechanisms (Hewett et al., 2013).

In the current study, it appeared that there might be a potential prophylactic effect with more generalised muscular co-contraction pattern adaptation in the medial and lateral musculature of the knee joint. In regarding the SLL task there was a non-significant improvement in the medial musculature of the knee joint (VM-ST) during the feed-forward motor control phase; 42% on average when compared with their baseline values. Nonetheless, an increased level of motor activation at the lateral knee joint (VL-BF) during the feed-forward motor control phase: 70% on average when compared with their baseline values. This might result in general improvement in muscle recruitment pattern balance, which may have been reflected in improving the knee joint stability and a better ability to counter valgus loads during demanding physical activities (Palmieri–Smith et al., 2009). Therefore, non-significant improvements in the medial to lateral co-contraction muscular activation ratio was observed during the feed-forward motor control phase, which showed an increase on average of 24% when compared with their baseline values in comparison to their baseline values, as a consequence to previously mentioned alteration in medial and lateral muscular recruitment pattern.

During the feedback motor control phase there was selective musculature co-contraction pattern adaption in the medial and lateral musculature of the knee joint. Whilst, the level of motor activation at the medial knee joint (VM-ST) showed non-significant increase by 12.7% on average when compared with their baseline values, whereas, the level of motor activation at the lateral knee joint (VL-BF) showed non-significant reduction by 95% on average when compared with their baseline values. Thereby, as a consequence to previously mentioned alteration in medial and lateral muscular recruitment patterns a reduction at the medial to lateral co-contraction muscular activation ratio was observed during the feed-forward motor control phase. However, even though the outcomes of muscular activation of the knee showed non-significant increase in knee medial and lateral muscular co-contraction index during the feed-forward motor control phase by 13.8%MVIC and 16.8%MVIC, respectively. Those muscular recruitment patterns were more than the knee medial and lateral muscular co-contraction index during feed-forward motor control phase MDD values of 13.4% MVIC and 9.9% MVIC reported previously in the reliability study in Chapter Three in section 3.2.7.3. This may have indicated that the low sample size may be the main reason for lack of significance.

In regards the SLS task there was no significant changes observed. However, increases in muscular co-contraction at the medial knee (VM-ST) and even at the lateral knee (VL-BF) by 16% and 28%, respectively, when compared with their baseline values, were seen. This resulted in an overall improvement in medial to lateral co-contraction muscular activation ratio by an average 16% on average when compared with their baseline values. This was more superior to the alteration in overall improvement in medial to lateral co-contraction muscular activation ratio during SLS task with the walking group in the main study in Chapter Five which demonstrated a slight decrease by 1.7% on average when compared with their baseline values. Similar to kinematic data this may be due to the nature of the sample population who have higher potential for ACL injury in their contralateral knee. Thus, it may reflect in a greater response to study intervention (Myer et al., 2007, Lim et al., 2009). However, even though there was observed alteration in muscular recruitment trends none reached a significant level. The main reason for lack of significance was mostly related to low sample size of participants in the study.

In summary, the EMG outcomes from the current study suggested that the incorporation of the AposTherapy system may induce positive changes in the muscle recruitment pattern of the contralateral lower limbs in individuals who previously sustained ACL injury and had ACLR. However, no significant changes were observed. Therefore, in conclusion, both null hypotheses are accepted because there was no significant change in the muscular co-contraction index of the medial and lateral musculature of the knee joint.

6.7.4 Patients reported outcomes.

- Hypothesis 6: There is no significant difference in patients reported outcomes (KOOS), before and after the AposTherapy intervention.

The effect of the implementation of AposTherapy intervention on the study participants showed general improvement in their KOOS outcomes. This was mostly observed in the KOOS (QOL) subscale that showed significant improvement, (24.33% on average when compared to their baseline values). Even though there is a general trend of improvement in other KOOS subscale, which included pain, symptoms and sport recreation activity none showed significant changes. The observed changes in reporting by participants reflected in particular that they are more confident in using their contralateral knee during sport participation, which may be related to the improvement shown in participant’s lower limb biomechanical parameters, such as knee valgus motion and postural stability.

In summary, the current study outcomes suggested that the introduction of AposTherapy system may result in improvements in KOOS questionnaire outcomes observed at the end of the intervention in the young active individuals, with high risk of second ACL injury. However, significant changes were only observed in QOL subscale. Therefore, in conclusion, hypotheses are partially accepted because there was only significant improvement in QOL subscale. Interestingly, four of the study participants said they noticed much improvement in their lower limb function and regained trust to execute single leg manoeuvres while participating in sports activities, which they could not post their ACL injury and even post ACLR. That eventually gave them more willingness to use AposTherapy. Therefore, in conclusion, hypotheses are partially accepted for only during the KOOS QOL and rejected for the rest of KOOS subscales.

6.8 Limitations.

The results of this study may be subject to several limitations. Firstly, the study included the small population, which limited the statistical power of the results leaving open the possibility that there might have detected differences with a larger sample. This was due to the logistical and time restrictions of our thesis. Secondly, the ipsilateral side (ACLR knee) was not assessed, nor was lower limb side-to-side imbalance in terms of strength and muscle recruitment strategies; movement mechanics, which is considered one of the risk factors for sustaining a second ACL (Paterson et al., 2010; Alarifi et al., 2017). Thirdly, the investigation only included observation of the short-term effects of the AposTherapy intervention; it is not known how long the effect of the intervention will last. However, it could be argued that the athletes could continue using the device during the pre-season and in-season period because it has a low-intensity simple nature. Fourthly, owing to logistical complexity and limited funds, it was not possible to increase the degree of perturbation by upgrading to pods with a greater degree of convexity to replace the ones installed at the customisation session at the beginning of the study, to progress the perturbation challenge – a step that may have improved the study outcomes. Fifthly, the effect of the menstrual cycle was not taken into consideration for the female subjects who participated in this study. The influence of different sex hormones on mechanical properties especially during the menstrual cycle have been considered a factor which may alter the recruitment pattern of muscular of lower limbs (Herzberg et al., 2017; Casey et al., 2014; Lefevre et al., 2013; Smith et al., 2012). Sixthly, there was no control group with matching age and skills recruited. Finally, higher levels of medial to lateral Q and H co-contraction would be essential for dynamic knee stabilisation. However, a large increase in Q and H co-contraction may lead to high compression forces on the knee articular cartilage, which may eventually initiate articular cartilage degeneration (Hubley-Kozey, 2009; Hall et al., 2010). Until now it is ambiguous to what degree correction would be safe degree to reduce valgus loads. Bennell et al. (2011) showed that higher dynamic medial knee loads would predicts greater cartilage loss in medial knee osteoarthritis over 12 months.

6.9 Conclusion.

The aim of this study was to investigate the effect of applying the biomechanical footwear device the AposTherapy system on lower-limb postural stability, kinematics, kinetics, and electromyography measures in individuals who have previously sustained NCACL injury and had reconstruction operations, and who still demonstrated poor neuromuscular control of their lower limbs, especially on their contralateral side. Even though, this study was with a small sample size, there were promising outcomes exhibited with the use of the AposTherapy system in ACLR individuals with potential risk of sustaining second ACL injury at contralateral limb. This might represent a time efficient simpler method that may easily be implemented with the standard post-ACLR rehabilitation programs to risk mitigate persistent poor neuromuscular control and movement mechanics. Therefore, it may be justified that a larger study with an appropriate control group/intervention should be undertaken to examine whether AposTherapy system has a better effect than a control group.

CHAPTER SEVEN: Overall Conclusions and Future Studies

7.1 Summary.

The aim of this thesis was to investigate the effectiveness of the ApósTherapy system on lower limb biomechanics, muscular recruitment pattern and postural stability within a recreational female athletes population at high risk for sustaining primary ACL injuries, as well as among recreational athletes who had ACL reconstruction at high risk of sustaining a second ACL injury at contralateral limb during sport activities.

In chapter two, the focus was on a comprehensive review of the existing literature linked to ACL injury risk factors, including anatomical, hormonal, neuromuscular and biomechanical. With the emphasis on modifiable risk factors for ACL injury, particularly knee joint frontal plane variables. Moreover, a literature review was carried out for the last three decades covering prevention programs implemented to reduce ACL injury rates or to reduce risk of injury. Several ACL injury intervention programs were covered that applied difference strategies and utilised various training components such as plyometric, balance, strength, stretching, and agility exercise elements.

In addition, focus was placed on proprioception and balance training, as this sole attractive component provides low-impact intensity with similar effects as multiple-component, high-intensity and time-consuming intervention programs. The review concluded that incorporation of unstable devices in the balance training programs may reduce the risk of sustaining ACL injury during high demanding athletic activities. Thus, unstable footwear device, have been documented to be used in NMT and showed strong potential to improve lower limb neuromuscular control, thus enhance knee dynamic stability. However, several limitations where documented, as unstable footwear were unable to manipulated individual's lower limb alignment. In addition, the majority only produce perturbation in one direction, which may have limited the potential prophylactic effects.

The potential utilisation of the novel biomechanical footwear device (ApósTherapy system) for prevention intervention amongst high-risk recreational female athletes and the potential of incorporating the device in post-ACL reconstruction rehabilitation program to reduce the risk of contralateral ACL injury. This was due to inefficient post-ACL reconstruction rehabilitation program, which still put them in high risk when the return to their pre-injury sport levels.

Furthermore, the current evidence regarding the AposTherapy system was reviewed, as it demonstrated an ability to alter the lower limb alignment beside introducing of perturbation at same time, which been documented to alter the loads on the knee joints among subjects with osteoarthritis and healthy male individuals as well as to successfully introduce control destabilisation for lower limbs. This result revealed an attractive concept that may offer a prophylactic effect on reducing the risk for sustaining ACL injury. Therefore, the thesis aimed to answer whether knee valgus motion, moments and muscle co-contraction measures during SLS and SLL tasks and also postural stability during single leg stance were altered after the incorporation of AposTherapy system for a six-week period.

Chapter three detailed the majority of the methodological techniques utilised as well as a reliability study for these measures. This study was an important addition to the current research and will enable other researchers to avoid measurement errors in their results. A reliability study, including the functional tasks employed in this study, was carried out before the studies performed in this thesis.

In chapter four, as the device had not previously been trialled among the ‘at-risk’ population, a feasibility study investigated whether using the AposTherapy intervention during a six-week period would be possible for five recreational female athletes who had shown a high-risk indication for sustaining a non-contact ACL injury. This feasibility study involved the main study methodology and the response of the participants to the recruitment methods utilised. Additionally, the researcher assessed their responses to the study intervention program as well as the logistics employed to best work out the screening, calibration and pre-post assessment. This was the first study to demonstrate the feasibility of incorporating AposTherapy as an intervention to mitigate the risk for primary ACL injury in high-risk adult female recreational athletes who demonstrated poor neuromuscular control. Furthermore, this is the first study to demonstrate a significant instant increase in postural instability while wearing AposTherapy system.

Chapter five detailed a pilot randomised clinical trial involving three groups, including a control with participants continuing doing their routine without any interference, and two study groups with active intervention groups who wore the device for period of six weeks to determine the changes in biomechanical and muscular recruitment patterns for quadriceps and hamstring. In addition to the changes in measures of posture stability, this study was an important addition to current research on risk mitigation for ACL injury among adult female recreational athletes with poor neuromuscular control. The study showed promising outcomes with participants who only used the simple version of intervention, i.e., just using the ApopsTherapy system for walking while preforming usually daily activities. They demonstrated a reduction in knee valgus coupled with improvements in muscle co-contraction of quadriceps and hamstrings, as well as enhanced postural stability, all of which are important risk factors increasing stress on ACL during sports activities.

This study has revealed that more simple, easy and low-impact interventions may be useful for risk-mitigation programs in reducing ACL injury risk among the high-risk female athlete population. This outcome encourages us to expect similar or better outcomes when incorporating AposTherapy system among adult recreational athletes who had previously sustained a NCACL injury, who had a reconstruction operation and who still demonstrated poor neuromuscular control of their lower limbs, especially on their contralateral side. Therefore, conducting a pilot study was suggested incorporating AposTherapy system just during walking while doing daily activities among individuals who had primary ACL reconstruction and at high risk for a second ACL injury to their contralateral lower limb.

In chapter six, a short pilot study was presented regarding risk mitigation following primary ACL reconstruction among individuals who still demonstrated poor neuromuscular control of their lower limbs, especially at their contralateral side. Thus, where deemed at risk of a second NCACL on their contralateral limb. The five participants in the study were incorporated into a six-week intervention program, wherein they were instructed to just wear the devise for walking during their daily activities. The results demonstrated positive outcomes, with a reduction in knee valgus motion and improvement in postural stability. In addition, participants in the pilot study reported improvement in their ability to pre-participate in their sports and/or recreation activities. The results of this pilot study support our postulation that the incorporation of AposTherapy in late rehabilitation stages may have a prophylactic effect in reducing the risk of a second ACL injury.

7.2 General Discussion.

The ACL injury is considered one of the most devastating knee injuries which could happen to any young athlete (Alentorn-Geli, 2009; Shultz et al., 2012). ACL injury would have short and long term morbidity consequences with high risk of developing premature osteoarthritis in early age, with all the negative impact that have in the individual wellbeing and health-system (Neuman et al., 2008; Gianotti et al., 2009). There are various biomechanics risk factors for ACL injury been studied. However, knee valgus has been identified as the primary predictor for both primary ACL and second ACL injury in high risk active population (Hewett et al., 2005; Krosshaug et al., 2007; Koga et al., 2010; Paterno et al., 2010). Many prevention programs been developed and introduced to reducing ACL injury risk (Michaelidis et al., 2014; Stevenson et al., 2015; Sugimoto et al., 2016; Volpi et al., 2016). However, the majority of NMT programs required a huge time commitment and had a considerable level of complexity and intensity. This appeared to deter athletes and reduced their adherent rates (Sugimoto et al., 2013; Stevenson et al., 2015).

This brought up the need for a simpler yet effective intervention to be developed. Therefore, it was proposed to incorporate footwear biomechanical device such as the AposTherapy system into ACL injury prevention program. The AposTherapy system previously been used in osteoarthritis patients and shown ability to reducing pain and improve the patient's functional measures. The AposTherapy system allow manipulating knee alignment to reduce loads on the knee and at the same time introduce perturbation for motor learning (Haim et al., 2008, 2010).

To carry on the work and test the hypothesis several studies were conducted through this thesis (Figure 7-1). In chapter four a feasibility study tested the feasibility to implant the AposTherapy system in NMT program in cohort of recreational female athletes. This study tested if it's safe wearing the AposTherapy system while performing exercise. The outcomes of the feasibility study showed that it was safe to use the AposTherapy system while training and head high compliance rate. Moreover, improvement in maximum knee valgus angle and other biomechanical risk factors were observed (Table 4-2 to 4-9), showing several values that exceeding SEM and MDD values previously reported in reliability study (Chapter Three in section 3.2.7.2-4). Even though the finding from the feasibility study show the potential of the AposTherapy system to induce biomechanical and muscular recruitment changes.

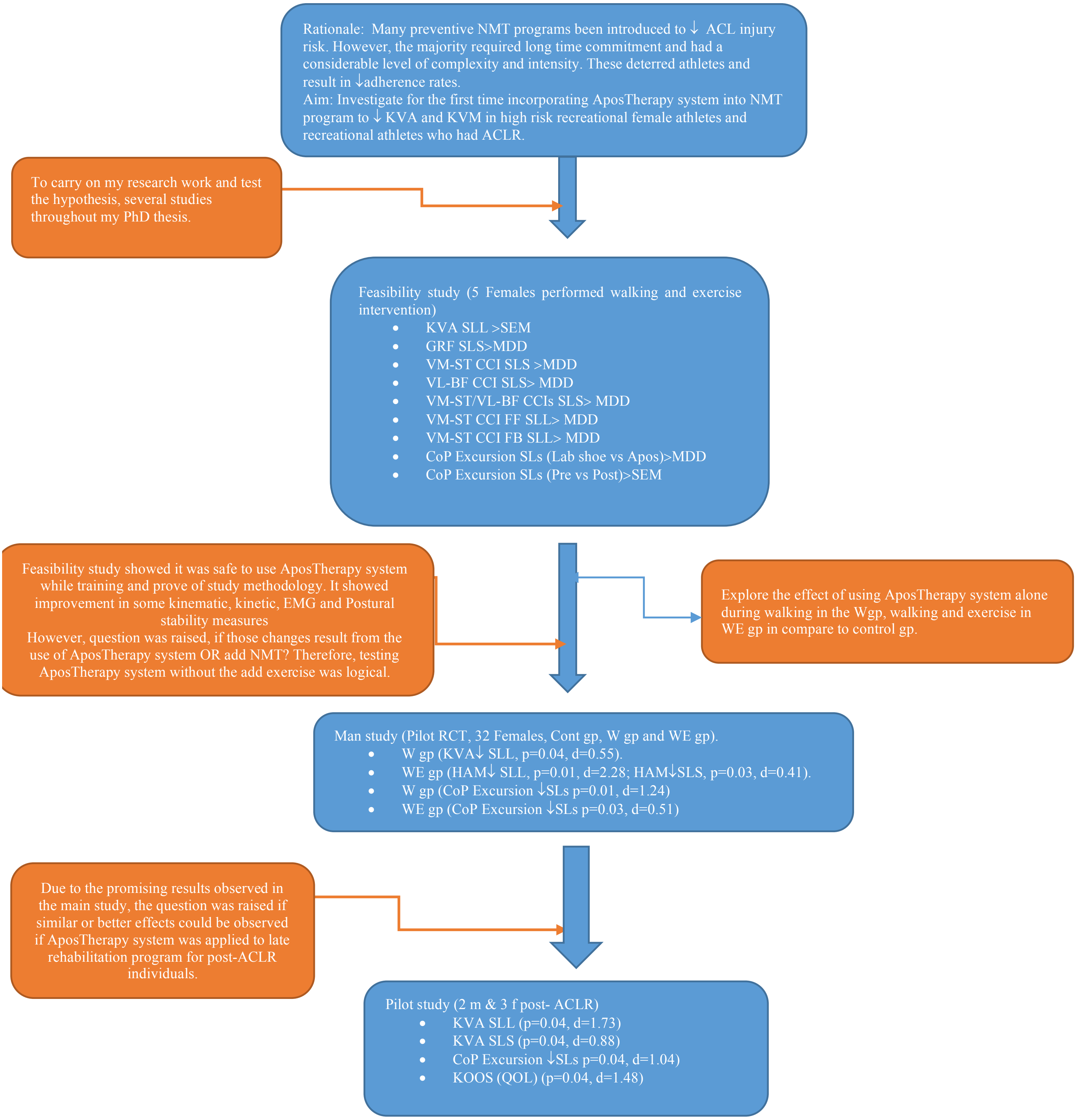
However, it was not clear whether those changes would be due to effect of the AposTherapy system or to exercise components alone, into the study intervention which needs to be assessed. The outcomes of this feasibility study were promising but not conclusive because of the lack of sufficient participant's sample size.

Therefore, a larger study was justified. In chapter five a main study was designed as a pilot RCT study that has three study groups. The main study was conducted to explore the effect of using the AposTherapy system only or with exercise on high risk recreational female's athletes. Interestingly, there was a group-selective improvement in the frontal plane. Maximum knee valgus angle during SLL task was significantly reduction in walking group participants (Table 5-2), whereas a significant reduction in maximum hip adduction moment was observed during the performance of SLL and SLS functional tasks (Table 5-12 and 5-16). This improvement in the frontal plane at the hip joint level in participants in the walking and exercise group may be attributed to the nature of the study intervention, with the added exercise component improving the hip abductor muscle activation pattern and strength that could be related to the incorporation of multiple exercise to a high level of difficulty (Hewett et al., 2016; Ortiz et al., 2010; Zebis et al., 2008). In addition, improvement in postural stability measures was observed in both intervention groups. However, the walking group showed higher effect size when compared with walking and exercise group (Table 5-27).

The outcomes showed the ability of the device to reduce knee valgus motion while wearing it only without additional exercise. This finding is promising as the use of unstable footwear such as the AposTherapy system could offer a simpler yet efficient supplement to the NMT programs. Similar to other unstable footwear such as the (RBS) (Kubota et al., 2015) and (MBT) (Landry et al, 2010) which demonstrate ability to improve the lower limb neuromuscular control the AposTheray system showed promising outcomes too. Yet, the AposTherapy system is more a flexible and dynamic device in compared to the static balance training devices and unstable footwears which make it a better option as it allows customize adjustment of the lower limb alignment in more than one movement plane. The draw back with the AposTherapy system would be its high cost, which may be an obstacle from it been implemented on large scale prevention programs young recreational female athlete population. Yet, this would not be an issue for elite female athletes. However, the effect of the AposTherapy system on elite athletes has not been tested.

As a growing body of evidence demonstrated a high risk of sustaining a second ACL injury in young individuals who had ACLR, in particular in their contralateral limb due to predisposing biomechanics and muscular recruitment patterns in the lower limb (Paterno et al., 2010; Hewett et al., 2013). Therefore, in a preliminary study the thesis examined the effect of implementing the AposTherapy system in cohort of post-ACLR young individuals who demonstrated high FPPA in their contralateral limb. The outcomes demonstrated the ability of the AposTherapy system to reduce knee valgus during SLL and SLS with a significant large (d=1.73 and 0.88, respectively) decrease in the maximum knee valgus angle. In addition, a significant improvement in postural stability measures with significant large (d=1.04) decrease in the CoP excursion. This all may explain significant large (d=1.48) increase in KOOS (QOL) subjective measures which may reflect improvement in participant's functional abilities. When considering that knee valgus motion and postural stability been documented to be one of the predictive risk factors for sustaining second ACL injury (Paterno et al., 2010; Howells et al., 2011; Heinert et al., 2018) these outcomes could be very promising. It is important to ensure that both limbs during post-ACLR received adequate rehabilitation to improve their mechanics before allowing the patients to return to functional activities (Heinert et al., 2018; Hewett et al., 2016; Paterno et al., 2010). This may be were a device such as the AposTherapy system may fit into the late stage of post-ACLR rehabilitation prior to return to sport activities. Targeted rehabilitations for post-ACLR patients are likely most effective when tailored to patient's specific lower limb biomechanics and neuromuscular deficits (Barber-Westin, 2011; Hewett et al., 2013). However, a larger study with sufficient sample size and control group would be justified.

Figure 7-1: Theoretical diagram of thesis.



Rationale: Many preventive NMT programs been introduced to ↓ ACL injury risk. However, the majority required long time commitment and had a considerable level of complexity and intensity. These deterred athletes and result in ↓adherence rates.
Aim: Investigate for the first time incorporating AposTherapy system into NMT program to ↓ KVA and KVM in high risk recreational female athletes and recreational athletes who had ACLR.

To carry on my research work and test the hypothesis, several studies throughout my PhD thesis.

Feasibility study (5 Females performed walking and exercise intervention)

- KVA SLL >SEM
- GRF SLS>MDD
- VM-ST CCI SLS >MDD
- VL-BF CCI SLS> MDD
- VM-ST/VL-BF CCIs SLS> MDD
- VM-ST CCI FF SLL> MDD
- VM-ST CCI FB SLL> MDD
- CoP Excursion SLs (Lab shoe vs Apos)>MDD
- CoP Excursion SLs (Pre vs Post)>SEM

Feasibility study showed it was safe to use AposTherapy system while training and prove of study methodology. It showed improvement in some kinematic, kinetic, EMG and Postural stability measures
However, question was raised, if those changes result from the use of AposTherapy system OR add NMT? Therefore, testing AposTherapy system without the add exercise was logical.

Explore the effect of using AposTherapy system alone during walking in the Wgp, walking and exercise in WE gp in compare to control gp.

Man study (Pilot RCT, 32 Females, Cont gp, W gp and WE gp).

- W gp (KVA↓ SLL, p=0.04, d=0.55).
- WE gp (HAM↓ SLL, p=0.01, d=2.28; HAM↓SLS, p=0.03, d=0.41).
- W gp (CoP Excursion ↓SLs p=0.01, d=1.24)
- WE gp (CoP Excursion ↓SLs p=0.03, d=0.51)

Due to the promising results observed in the main study, the question was raised if similar or better effects could be observed if AposTherapy system was applied to late rehabilitation program for post-ACLR individuals.

Pilot study (2 m & 3 f post- ACLR)

- KVA SLL (p=0.04, d=1.73)
- KVA SLS (p=0.04, d=0.88)
- CoP Excursion ↓SLs p=0.04, d=1.04)
- KOOS (QOL) (p=0.04, d=1.48)

7.3 Thesis novelty.

This PhD thesis is the first study to explore the effect of a novel biomechanical foot-worn device (AposTherapy system), which provides both perturbation and biomechanical adaptations for the wearer without the burden of interfering with the athlete’s busy schedule and it been simple to use. The overall aim of the thesis was to determinate the effect of the AposTherapy system on lower limb biomechanics and muscular recruitment patterns while performing two functional tasks (performance single-leg squat and single-leg landing functional tasks). In addition, to observing the changes in postural stability measures while performing single leg stance task.

This thesis is the first study to demonstrate the feasibility of incorporating the AposTherapy system, as intervention program in high risk recreational female athletes. Furthermore, it is the first study which explored the ability of the AposTherapy system to reduce maximum knee valgus motions in high risk recreational female athletes. In addition, this is the first study which investigated the ability of AposTherapy system to reduce peak knee valgus motion in young recreational post-ACLR athletes.

This study found that participants who finished post-ACLR rehabilitation programs and been declared ready to return to sports still show poor control of lower limb motion when screened. These would agree with previous studies which highlighted the need to use easily administrated quantitative tests that can capture relevant high risk movement mechanics should be warranted. However, this would be beyond the scope of the present thesis and it is something which would need to be determined in future research. The, overall finding in this thesis will add to the knowledge for both clinicians and researchers in the field of risk mitigation of ACL injuries in high-risk populations. Additionally, it is a small step in the framework for mitigating risk factors in recreational female athletes at risk of an NCACL injury and post-ACLR young recreational athletes to utilise novel foot-worn devices (AposTherapy system).

7.4 Future studies.

This study demonstrated that utilising the AposTherapy system by wearing it during daily activities may have a promising influence on knee valgus motion and moments in young adult recreational female athletes and individuals who had ACLR. Moreover, it indicates improvements in motor activation patterns which may enhance knee dynamic stability during landing.

According to the positive biomechanical effect of incorporating the AposTherapy system among adult female recreational athletes, the result may have been better if the intervention was used in the pre-adolescent female population which been considered time before growth spurt. Therefore, future research should investigate participants of a younger age and different skill levels over a period of time to observe the effect over time. In addition, future research work should evaluate the muscle recruitment pattern of other lower limb muscle, which may include hip abductors and other knee flexors, as influencing knee valgus motion and loads. In this way, Gluteus Medius and Gastrocnemius muscle recruitment patterns may be investigated in future studies incorporating the AposTherapy system as a risk-mitigation intervention. Furthermore, the high cost of the device may suggest it potential to be used by professional athletes. This may justify conducting a study in the near future on professional female athlete's population to investigate the AposTherapy system effect on their lower limb movement mechanics especially with the promising result shown in this thesis.

In this thesis, studied the effect of wearing the AposTherapy system while performing single-leg squats and single-leg landing functional tasks only. However, it would be advisable to evaluate the effect of AposTherapy intervention while performing other functional tasks such as side-cutting task, drop vertical jumps and even during single-leg landing from heights of 40 cm as this would reveal different pattern of loads on the knee joint. Even though female athletes have been documented as suffering from a higher risk of NCACL injury on the non-dominant side, it would be recommended for future studies to investigate both lower limbs given that side-to-side differences in neuromuscular recruitment and biomechanics have been reported for the risk factors of NCACL injury in the female athlete population. Additionally, as muscles contribute to joint stability, neuromuscular fatigue is often suggested as a risk factor for NCACL injury. Therefore, it would be valid to conduct future research to examine the effect of the AposTherapy interventions while performing functional tasks per muscular fatigue, as athletes are more vulnerable to sustaining injuries while they are fatigued.

The study in chapter six suggests that the AposTherapy system may be an appealing intervention among young active individuals for post-ACL reconstruction rehabilitation to address the persistent neuromuscular imbalance to reduce the risk of sustaining a second

ACL injury at the contralateral leg after return to sports. The results of the study in chapter six were promising enough to justify conducting a study with a sufficient sample size, including a control group, to thoroughly investigate the biomechanical and muscular co-contraction of agonist and antagonist knees. However, both lower limbs should be investigated as side-to-side differences are considered one of the main risk factors for a second.

Finally, the results of the PhD study have demonstrated that the use of a perturbation training-based footwear devise with the ability to alter knee movements may be an alternative concept. the concept of providing both perturbation and biomechanical adaptation to the wearer without the burden of performing exercises using a biomechanical device in the form of footwear has given rise to the potential for the development of a device that is based on the same concept, but more flexible, simple, and cost effective initially named the (E-J unstable dynamic footwear) .In addition, the ability to be objectively customised also makes it a promising option have been brought up as results of this PhD thesis research work, which could be developed in the near future. The development of this footwear should be appealing with the main aim to offer a cheap devise which could be implemented on large scale prevention programs. Nevertheless, it also could be used for non-operative treatment of symptomatic osteoarthritis patients. In addition, it could also be used in post ACL reconstruction patient’s rehabilitation.

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APPENDICES

Appendix One

Research, Innovation and Academic
Engagement Ethical Approval Panel

College of Health & Social Care
AD 101 Allerton Building
University of Salford
M6 6PU

T +44(0)161 295 7016
r.shuttleworth@salford.ac.uk

www.salford.ac.uk/

12 April 2014

Dear Ihab,

RE: ETHICS APPLICATION HSCR13/69 – Effects of using Apostherapy system as an intervention to improve neuromuscular control in female athletes with a high risk for non-contact Anterior Cruciate Ligament (ACL) during jumping and landing manoeuvres

Based on the information provided by both you and your supervisor, Prof Jones I am pleased to inform you that application HSCR13/69 has now been approved.

If there are any changes to the project and/ or its methodology, please inform the Panel as soon as possible.

Yours sincerely,

Rachel Shuttleworth

Rachel Shuttleworth
College Support Officer (R&I)

Appendix Two

Research, Innovation and Academic Engagement Ethical Approval Panel

Research Centres Support Team
G0.3 Joule House
University of Salford
M5 4WT

T +44(0)161 295 2280

www.salford.ac.uk/

25 January 2017

Dear Ihab El-Zein,

RE: ETHICS APPLICATION– HSR1617-40 - The role of Apostherapy in improving neuromuscular control in athletes with a high risk for second non-contact Anterior Cruciate Ligament (ACL) injury after primary ACL reconstruction.

Based on the information you provided, I am pleased to inform you that application HSR1617-40 has been approved.

If there are any changes to the project and/ or its methodology, please inform the Panel as soon as possible by contacting Health-ResearchEthics@salford.ac.uk

Yours sincerely,

Sue McAndrew
Chair of the Research Ethics Panel

Appendix Three

Participants follow-up sheet

Participants name: **Intervention group:**

Session number	Session duration		intervention week
	Walking duration	Exercies duriation	
1			1
2			1
3			1
4			1
5			1
6			1
7			1
8			2
9			2
10			2
11			2
12			2
13			2
14			2
15			3
16			3
17			3
18			3

19			3
20			3
21			3
22			4
23			4
24			4
25			4
26			4
27			4
28			4
29			5
30			5
31			5
32			5
33			5
34			5
35			5
36			6
37			6
38			6
39			6
40			6
41			6
42			6

Appendix Four

Reliability study data

2D FPPA

Session 1st		Session 2nd	
Rt Mean±SD	LT Mean±SD	Rt Mean±SD	Lt Mean±SD
11.08±4.88	11.16±4.45	12.27±5.27	11.66±5.30

3D Kinematics and Kinetics results of the non-dominant leg during Single Leg Squat SLS.

Variables (SLS)	Session 1st	Session 2nd	Session 3rd
Joint angle (Degrees)			
Hip adduction angle	10.50±6.84	10.02±8.27	9.51±8.74
Hip flexion angle	77.38±11.91	77.71±15.71	83.48±9.32
Hip internal rotation	6.73±6.37	4.61±3.67	4.82±8.41
Knee valgus	-4.01±3.46	-3.79±3.67	-4.77±5.11
Knee flexion	79.74±8.71	83.89±11.53	83.48±9.32
Dorsiflexion	35.63±4.68	4.61±3.67	38.07±5.39
Joint moments (Nm/kg)			
Hip adduction	0.98±0.28	0.94±0.27	0.82±0.22
Knee valgus	0.08±0.05	0.12±0.09	0.13±0.07
Knee flexion	1.80±0.21	1.84±0.34	1.76±0.32
Dorsiflexion	1.04±0.14	1.15±0.27	1.17±0.18
Ground reaction force (Body weight)	1.12±0.03	1.13±0.04	1.16±0.07

3D Kinematics and Kinetics results of the non-dominant leg during Single Leg landing SLL

Variables (SLL)	Session 1	Session 2	Session 3
Joint angle (Degrees)			
Hip adduction angle	4.88±7.78	7.37±5.82	5.61±8.84
Hip flexion angle	69.10±9.59	74.05±12.35	66.57±11.48
Hip internal rotation	6.85±4.84	5.80±5.27	3.97±6.65
Knee valgus	-5.26±3.14	-5.54±4.12	-8.58±3.37
Knee flexion	74.56±5.97	74.53±6.38	75.55±6.51
Dorsiflexion	31.19±3.22	30.38±8.28	39.99±8.33
Joint moments (Nm/kg)			
Hip adduction	1.21±0.27	1.15±0.32	1.19±0.34
Knee valgus	0.23±0.11	0.22±0.11	0.24±0.09
Knee flexion	2.17±0.34	2.09±0.46	2.17±0.31
Dorsiflexion	1.67±0.31	1.69±0.43	1.81±0.43
Ground reaction force (Body weight)	2.41±0.40	2.32±0.42	2.34±0.44

Electromyography results:

The Electromyography results of the non-dominant leg during Single Leg landing SLL.

Variable	SLL Task phases	Session 1 Mean ±SD (% MVIC)	Session 2 Mean ±SD (% MVIC)
VM-ST CCI	Feed-forward phase	37.63±13.18	29.81±10.09
	Feed-back phase	45.18±20.52	36.01±19.32
VL-BF CCI	Feed-forward phase	49.45±16.39	41.18±17.88
	Feed-back phase	41.63±13.61	44.09±22.72
Med/ Lat ratio	Feed-forward phase	0.95±0.35	1.01±0.41
	Feed-back phase	0.89±0.52	0.93±0.74

The Electromyography results of the non-dominant leg during Single Leg Squat SLS.

Variable	Session 1 Mean ±SD (% MVIC)	Session 2 Mean ±SD (% MVIC)
VM-ST CCI	42.54±20.34	32.95±12.83
VL-BR CCI	47.81±21.63	48.81±21.53
Med/ Lat ratio	1.03±0.7	0.90±0.82

The CoP excursion results of the non-dominant leg during Single leg Stance.

Variables	Session 1 Mean ±SD (mm)	Session 2 Mean ±SD (mm)
CoP Excursion	45.09±27.63	35.63±13.35

Appendix Five

Research Participant Consent Form

Title of Project: The role of incorporating AposTherapy System on lower limb biomechanics in recreational female athletes with potential high risk for non-contact ACL Injury-Intervention study.

Ethics Ref No:

Name of Researcher:

(Delete as appropriate)

- I confirm that I have read and understood the information sheet for the above study and what my contribution will be and had the opportunity to ask and have answered my questions about the study.

Yes	**No**

- My participation in this research will involve a number of tests, which include Single Leg Squat, Single Leg Landing, and Single leg stance tests

Yes	**No**

- Ihab Elzein who is a Postgraduate research student at the University of Salford, has requested my participation in a research study. My involvement in the study and its purpose has been fully explained to me.

Yes	**No**	**NA**

- I understand that the results of this research may be published but that my name or identity will not be revealed at any time. In order to keep my records confidential, will store all information as numbered codes in computer files that will only be available to him

Yes	**No**	**NA**

- I have been informed that any questions I have at any time concerning the research or my participation will be answered by and I can contact him at (I.El-zein@edu.salford.ac.uk

Yes	**No**	**NA**

- I understand that my participation is voluntary and that I can withdraw from the research at any time **without giving any reason**

Yes	**No**

➢ I understand that if I withdraw from the study, then the data collected may be used for analysis purposes unless I request not to do so	**Yes**	**No**

➢ **I agree to take part in the above study**	**Yes**	**No**

Name of participant ………………………………………………………………………………

Signature ……………………………………………………………………………….

Date ……………………………….

Name of researcher taking consent ……………………………………………………………

Researcher's e-mail address ……………………………………………………………

Appendix Six

Research Participant Consent Form

Title of Project: The role of incorporating AposTherapy system on lower limb biomechanics in recreational athletes with a high risk for second non-contact ACL injury at contralateral limb, after primary ACL Reconstruction: Pilot study.

Ethics Ref No:

Name of Researcher:

(Delete as appropriate)

➢ I confirm that I have read and understood the information sheet for the above study (version 2.0-11/01/2017) and what my contribution will be and had the opportunity to ask and have answered my questions about the study .	**Yes**	**No**	
➢ My participation in this research will involve a number of tests, which include Single Leg Squat, Single Leg Landing, and Single leg stance tests	**Yes**	**No**	
➢ Ihab Elzein who is a Postgraduate research student at the University of Salford, has requested my participation in a research study. My involvement in the study and its purpose has been fully explained to me.	**Yes**	**No**	**NA**
➢ I understand that the results of this research may be published but that my name or identity will not be revealed at any time. In order to keep my records confidential, will store all information as numbered codes in computer files that will only be available to him	**Yes**	**No**	**NA**
➢ I have been informed that any questions I have at any time concerning the research or my participation will be answered by and I can contact him at (I.El-zein@edu.salford.ac.uk	**Yes**	**No**	**NA**
➢ I understand that my participation is voluntary and that I can withdraw from the research at any time **without giving any reason**	**Yes**	**No**	

- I understand that if I withdraw from the study, then the data collected may be used for analysis purposes unless I request not to do so

Yes	**No**

- **I agree to take part in the above study**

Yes	**No**

Name of participant ……………………………………………………………………………

Signature ……………………………………………………………………………….

Date ……………………………….

Name of researcher taking consent ……………………………………………………………

Researcher's e-mail address ……………………………………………………………