Factors that Influence the Performance of Hop Tests

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Abstract

Hop tests are useful measures of physical performance and athletic function, and they can also be used to monitor progress, as well as recommend whether a return to sport or normal activity is likely to be beneficial or harmful for those recovering from a sporting injury or surgical intervention. Hop tests can combine and test the different elements that may have been affected due to an injury, for example joint stability, muscle strength and neuromuscular coordination. There is limited literature exploring the factors which influence the performance of hop tests, and provides reference values for each of the individual test during different athletic tasks. A better understanding of these factors would offer a clear vision about what reflect the hop performance in both healthy and anterior cruciate ligament reconstructed (ACLR) participants during common screening tasks.

This thesis includes four themed studies. The first study aimed to investigate the reliability of the individual tests which consist of hop tests, two-dimensional (2-D) Frontal-Plane Projection Angle (FPPA), balance tests, force generation tests, and isokinetic strength testing to establish the measurement error of these. The findings of first study revealed that the majority of the intraclass correlation coefficients (ICC) values for all tests were excellent across all variables during within- and between-day sessions testing, showing these tests to be reliable. However, impulses from 0 - 100, 200, 250, 300 ms had less reliable variables across all isometric mid-thigh pull (IMTP) results.

The second study established the differences between right and left leg performances across all tests and to describe reference values for the limb symmetry index (LSI) for hop tests and isokinetic muscle strength tests for recreationally healthy participants. However, the main reason behind conducting this study was to identify whether one leg's performance can define the other and to determine the reference values in a heathy population, and further to this investigation, if the limbs were found to be symmetrical across all the tests, then the next study would be carried out using the right leg only. This study has concluded that no differences were found between right and left leg performance during all the tests. In addition, symmetry between limbs existed during both hop and isokinetic muscle strength tests, from which it can be concluded, that one leg's performance can define the other.

The third study examined the relationship between all of the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks in healthy participants. This would then also provide the reference values that are needed for each of the individual tests. The conclusion of this

element of the study is that force generation and ankle plantar flexion strength seem to be the most contributing factors to hop performance in a healthy population.

The final study aimed to examine the differences between injured and non-injured leg performances across all tests and describe reference values for the LSI for hop tests and isokinetic muscle tests in ACLR participants. Also, to investigate the relationship between all of the tests and hop performance during single-leg hop for distance and crossover hop tasks for the injured and non-injured limbs, and provide the reference values that are needed for each of the individual tests for both limbs. This study has found that dynamic force generation and both quadriceps and hamstring muscle strength seem to be the most contributing factors to hop performances for the injured limb, while the uninjured leg failed to show any association to hop performance and does not perform in a manner which could be regarded as normal.

This thesis has expanded that hop tests can be used in a clinic to indicate potential deficits in strength or force generation in lower limbs. Moreover, provided reference values in a physically active population and ACLR participants for hop tests and all the related tests. Also, demonstrated the relationship between all of the tests and hop performance tests in a healthy population and in ACLR participants. Lastly, established the drivers of hop performance are different in the ACLR limb and the non-injured limb compared to those in healthy.

Introduction

Hopping is a common task performed in many sports (Ross et al., 2002). Physical performance and athletic function can be measured using hop tests. Such tests are useful for monitoring progress and to decide whether the person is ready to return to sport or everyday activities following an injury or surgery (Phillips and van Deursen, 2008). There are different types of hop tests which measure various aspects that may be affected following an injury (Munro and Herrington, 2011), such as muscle strength (Noyes et al., 1991), the stability of the joints (Hertel and Olmsted-Kramer, 2007); in addition, testing both muscle strength and joint stability requires neuromuscular coordination and this mix should also be considered (Myer et al., 2004). Several different hop test protocols have been described and utilised in the sports literature (Noyes et al., 1991; Booher et al., 1993; Fitzgerald et al., 2001; Phillips and van Deursen, 2008). These hop tests involve many variations, such as a single hop for distance, figure-of-eight hop, lateral hop, side hop, shuttle run, up-down hop, agility hop test and triple crossover hop for distance.

When landing from a triple hop, the impact forces produced can reach a magnitude of up to twelve times the person’s body weight (Perttunen et al., 2000) and result in lower extremity injuries (Jacobs et al., 2007). Landing involves large forces being applied by the knee and hip extensors, and ankle plantar-flexors, to control joint flexion and decelerate the body (Mcnitt-Gray, 1993). When landing, the lower extremities help to absorb and dissipate the ground reaction forces resulting from each hop. If these forces are very large and the body cannot accommodate and control them, there is a risk of injury. Research has been conducted on jumping to try to understand how one generates and uses the energy needed to push oneself. In studies on landing, there has been a focus on the biomechanical implications of impact, and of the total load on lower limb tissues (Devita and Skelly, 1992). However, during different activities, the landing phase may be overlooked, which might contribute to poor performance or injury. Therefore, there has been an increased focus on the factors that contribute to different landing techniques (Dufek and Bates, 1991).

Anterior cruciate ligament (ACL) injuries have been theorised as being attributable to frequent landing from a hop that requires the subject to maintain their balance (Griffin et al., 2000). Balance can be defined as the ability to keep the centre of gravity of the body within the limits of the base of support (Cook and Woollacott, 2001). Different definitions have been used to describe the word balance, such as stability, dynamic postural control and postural control. It has been stated that balance may be the most important element of athletic ability

(Gambetta and Gray, 1995). However, maintaining the body's balance through joint stability results from a complex sequence of actions and reactions that work through different parts of the body (Riemann and Lephart, 2002). Balance testing is an important component in sports outcome measurements, but especially in the sports rehabilitation process, particularly where landing or maintaining balance is a key component of the activity. Time to stability (TTS) is a parameter that is used to measure dynamic stability when a subject moves from a dynamic phase to a static phase. Measurement of this outcome has been used in dynamic conditions to examine and compare ACL-deficient and healthy subjects (Phillips and van Deursen, 2008).

Knee injuries may result in reduced quadriceps and hamstring strength (Hiemstra et al., 2000), and ankle injuries may result in increased time to achieve stabilisation (Ross et al., 2005). Higher levels of lower limb strength will potentially result in improved performance (Myer et al., 2006), more controlled landings and a reduction in injuries (Jacobs et al., 2007). Previous studies have noted an association between concentric strength and hop distance (Hamilton et al., 2008); however, eccentric strength is reported to be important in lower limb function and rehabilitation following injury (Lorenz and Reiman, 2011). Moreover, landing requires large eccentric muscle forces to be exerted by the knee, hip and ankle extensor muscles during the control phase, when joints are in a flexed position, in order to decelerate the body (McNitt-Gray, 1993). Therefore, one of the most important indicators of athletic ability is muscle strength, and this is particularly important for sports involving a high generation of force over a short time (Newton and Kraemer, 1994).

Evaluating strength output during the Jump Squat (JS) activity has been considered as a common theme in the literature (Cronin et al., 2004; Dugan et al., 2004; Duthie et al., 2002; McBride et al., 2002). Furthermore, jumping requires complicated motor coordination between the upper and lower parts of the body, making it a complex movement (Markovic et al., 2004). This is particularly the case for professional athletes when it comes to the strong propulsion necessary during the vertical jumping required by certain sports (Bosco and Komi, 1979; Bosco and Viitasalo, 1982). For this reason, force generation was investigated in the study of West et al. (2011), in which the participants applied maximal IMTP, and the bend at the knee of approximately 120-130˚ as well as countermovement jump (CMJ). Force–time data were assessed for peak force (PF); peak rate of force development (RFD), and force at 100 milliseconds (F100ms). The PF during IMTP was found not to be correlated with dynamic performance (CMJ height), yet normalising the data to body weight revealed moderate correlations to CMJ height. In addition, moderate correlations were found between peak RFD during IMTP and CMJ height. The F100ms during IMTP was not related to CMJ height, however, when normalising the data of the F100ms to body weight, it was moderately correlated to CMJ height. Therefore, there is evidence from this research maximal strength and explosiveness values correlate to jump performance according to the isometric force-time data.

Kawamori et al. (2006) aimed to assess the relationship between IMTP force-time dependent variables and force characteristics of vertical jump (VJ) performances using a standard testing protocol. The data indicates that PF values of IMTP were strongly correlated with PF, peak RFD, and peak power of CMJ (r = 0.87, 0.85, and 0.95 respectively). However, peak RFD of IMTP had no correlations with vertical jump performances. Another study by Mcguigan et al. (2010) aimed to determine the relationships between measures of the IMTP force characteristics, which were PF and maximum RFD with VJ performance (height), in recreationally trained men. The results indicate that there were very strong correlations between VJ height and isometric med-thigh pull PF. However, there were no correlations with maximum RFD values. This study concluded that the PF during IMTP provides an efficient method for assessing VJ height in recreationally trained individuals.

Most ACL injuries, around 80%, are non-contact (Renstrom et al., 2008), for example, as a result of landing poorly from a high hop, or due to cutting movements or deceleration during sport. Hewett et al., (2005 pg.495) describe knee valgus as ‘the position or motion of the distal femur towards the midline and the distal tibia away from the midline of the body’ and it is one of the factors that contributes towards non-contact ACL injuries (Hewett et al., 2005), as well as other knee injuries (Heitz et al., 1999; Ireland, 1999). Knee valgus misalignment can be described as a postural dysfunction in the lower extremity while performing weight bearing exercise, such as the single leg squat (SLS) or single leg hop landing (SLHL), and it is fairly common. The SLS is ideal as a functional test due to it involving a dynamic movement which is required for a range of daily activities (DiMattia et al., 2005), for example stair climbing and running (eccentric knee flexion in a weight-bearing position); however, these movements also require muscle control due to their dynamic. According to Zeller et al. (2003) an increased knee valgus angle noted during SLS movement can occur with other movements, such as deceleration or landing, and this results in less control. Both three-dimensional (3-D) or 2-D motion-analysis systems are available for clinical research to measure functional movement, with 3-D seen as the gold-standard measurement tool for gait analysis (Whittle, 2007; Kirtley, 2006). Despite this, 3-D systems are expensive and require experienced operators (Rowe, 1999), therefore 2-D systems are more useful clinically.

Therefore, the aim of this project is to review the factors which may contribute towards hop performance in both the healthy and ACL reconstructed participants. From the literature, it can be seen that there are several factors which may be linked to hop performance, such as knee valgus angle, balance performance, generated forces, and lower limb muscle strength.

Chapter (1)

Literature Review

1 Chapter 1: Literature Review

1.1 Search Strategy

The literature relevant to this study was identified through a comprehensive search of online databases using the following search engines: AMED, CINAHL, Ovid-Medline, Google scholar and pub-med. Relevant links suggested by these databases were used to further extend the area of research. The strategy used to search the literature was limited to English language journals only, published in all countries, and related to human subjects. The main search terms used in the search strategy databases were: hop definition, hop performance, hop tests, single-leg hop for distance, crossover hop tests, 2-D knee angle valgus tests, FPPA, squat test, balance tests, TTS in Force Plate, postural sway in Force Plate, force generation tests, Ballistic Measurement System (BMS), squat jump (SJ) test, CMJ test, ten consecutive jumps test, IMTP test, concentric and eccentric muscle strength tests, Biodex System, muscle strength in landing, hop land forces, static balance tests, dynamic balance tests, knee frontal plane alignment, ACL injuries, and mechanism of ACL injury.

1.2 ACL Anatomy and Function

In order to reduce the likelihood of meniscal pathology, the ACL works to stop the anterior translation of the tibia on the femur, whilst allowing normal helicoid knee action. The ACL stretches widely from the anterior part of the tibia (between the intercondylar eminences), reaching a curved area on the posteromedial portion of the lateral femoral condyle (Kweon et al., 2013). The ACL plays a significant role in knee biomechanics. ACL function is essential to ensure that the dynamic stability of the knee joint is maintained to avoid hyperextension, which may occur during hopping, landing, cutting and pivoting manoeuvres (MacAuley, 2006). The main role of the ACL is to prevent anterior translation of the tibia (Kweon et al., 2013). Secondly, it can be seen as a stabiliser against the internal rotation of the tibia and knee valgus angle (Buoncristiani et al., 2006). In full knee extension, the ACL absorbs about 75% of the anterior translation load, and about 85% of the load absorbed between 30° and 90° of flexion (Butler et al., 1980). Therefore, any rupture of the ACL will lead to a decreased magnitude in this coupled rotation during an unstable knee and flexion movement (Kweon et al., 2013). The biomechanical properties of the ACL have been examined; however, it is impossible to determine uniform testing regarding strain rates and orientation (Kweon et al., 2013). It has been reported that the anterior bundles- both medial and lateral- reveal higher maximum strain and stress compared to the posterior bundles (Butler et al., 1991). The tensile strength of the ACL is around 2,200 N, but it differs with age and repetitive loads (Miller, 2000). The in situ force of the ACL increases as a result of the magnitude of the anterior shear force increasing (Smith et al., 1993).

The ACL is on average about 3cm in length and 1cm in diameter (see Figure 1.1) (Zantop et al., 2005). It starts at the posterior medial aspect of the lateral femoral condyle and is slotted in the anterior and lateral aspect of the medial tibial spine, and anatomically is subdivided into two main components: an anteromedial and a posterolateral bundle (Dienst et al., 2002). With regards to its function, the anteromedial fibers become rigid as the knee is bent, with the posterolateral fibers exhibiting tension as the knee is extended. The ACL has a blood supply mainly from the middle geniculate artery (Arnoczky, 1983). The innervation of the ACL is made up of mechanoreceptors from the tibial nerve and these contribute to its proprioceptive role (Biedert et al., 1992).

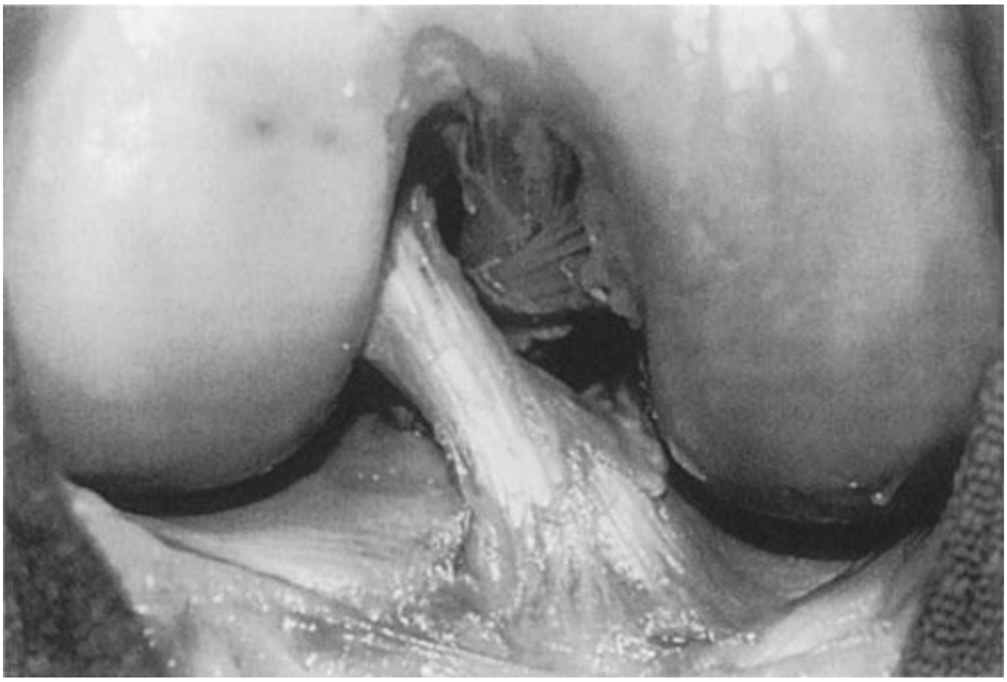


Figure 1.1. The ACL's complex helical arrangement and its broad attachment (Kweon et al., 2013)

1.3 Anterior Cruciate Ligament and the Mechanism of Injury

ACL is considered to be one of the most commonly injured ligament of the knee joint both nationally and internationally (Myer et al., 2004). With regard to ACL injuries, 80% have been shown to be non-contact in nature (Renstrom et al., 2008), occurring without any direct physical contact with the subjects' body. In addition, in young athletes, 48% to 96% of ACL injuries are reported to be non-contact in nature (Ferretti et al., 1992; Boden et al., 2000; Olsen et al., 2004). These types of injuries can occur under any condition, which causes the stress on the ACL to increase beyond its capacity (Hashemi et al., 2011). Unsuccessful landing manoeuvres, sudden deceleration, and cutting might be considered as possible factors in ACL injuries (Ferretti et al., 1992; Olsen et al., 2004). In earlier studies carried out to examine the rate of non-contact ACL injuries that are as a result of landing from a hop the figures ranged from 37% (Boden et al., 2000) to 73% (Ferretti et al., 1992); however, the studies were retrospective and had some limitations, because the data regarding the ACL injury was taken according to the subjects' recall, and difficulties arose in describing the positions of each segment accurately when the injury occurred. Usually, about 79% of ACL injuries occur during sports activities when athletes land on one leg (with whole body weight) in a position where the knee is at a slightly flexed angle (McNair et al., 1990; Ireland, 1999; Boden et al., 2000; Olsen et al., 2004).

An ACL injury can occur through two mechanisms, which are a contact (impact) or non-contact episode. A non-contact ACL injury may be described as an injury that has occurred without body-to-body contact (Myklebust el al., 2003). The rate of ACL injuries is fairly high in sport activities that require performing tasks such as jumping and landing from a jump, or rapid change in direction and decelerating; this includes netball, basketball, handball, and volleyball (Griffin et al., 2000).

Several studies have assessed the lower extremity joint angles through video analysis of ACL injured female athletes. They have reported that female athletes land with the hip in a flexed position, adducted and internally rotated, whilst the knee joint is near to full extension with the tibia externally rotated, and the foot hyper-pronated with a valgus knee collapse (Boden et al., 2000; Olsen et al., 2004). This position has been named dynamic knee valgus (Figure 1.2), or the position of no return (Ireland, 1999, Hewett et al., 2005).

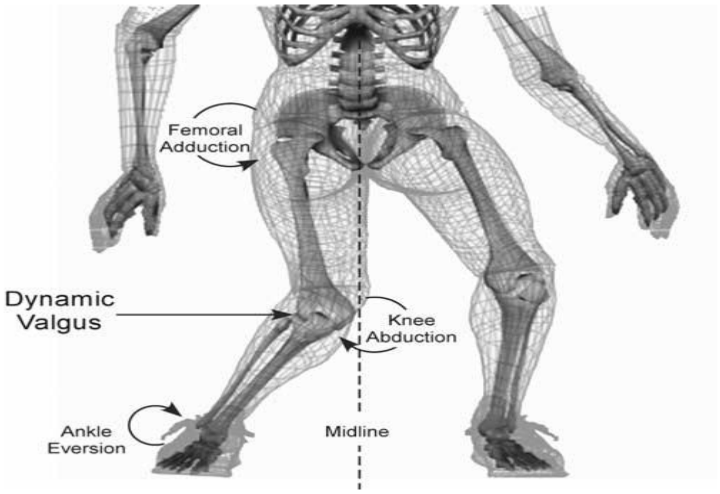


Figure 1.2. Illustrate the position of no return (Hewett et al., 2005)

1.4 Epidemiology for ACL injury

It has been reported in epidemiological research that female athletes are four to six times more at risk of ACL injuries in comparison to their male counterparts at a similar levels of the sport (Myklebust et al., 1998). The Centre for Disease Control and Prevention states that around 100,000 ACLR are carried out annually in the United States (Csintalan et al., 2008). The financial impact from ACL reconstructions has been estimated to be approximately $700 million per year, with total costs of around $17.000 per athlete for the surgery and full rehabilitation (Sugimoto et al., 2012).

Any ACL injury results in a prolonged period away from sports participation, regardless of the type of rehabilitation received, whether ACLR or conservative treatment. More than 50% of Swedish female footballers were unable to return to sport following an ACL injury, and only 15% returned to their pre-injury level of activity (Lohmander et al., 2004). In another study by Myklebust et al. (2003), only 58% of Norwegian elite handball players returned to their previous level of competition after ACL surgery, while 42%, either stopped playing at a professional level or returned to compete at a lower level.

These injuries require rehabilitation protocols including jumping and landing from a jump, or rapid change in direction and decelerating, in order to return to netball, basketball, handball, or volleyball (Griffin et al., 2000). Therefore, hop-land activity is considered one of the most important tasks that are related to non-contact ACL injury.

1.5 Biomechanical Risk Factors of Non-contact ACL Injury

Different biomechanical risk factors at the lower limb joints have been assumed to indicate the potential risk factor for ACL injury through non-contact mechanisms (McLean et al., 2004; Yu et al., 2006). These biomechanical risk factors include decreased flexion angle in the knee and hip joints at initial contact, high peak vertical ground reaction force during landing, increase in the peak knee valgus angle/moment, increase in hip adduction angle/moment, and increased rotation force at the knee and hip joints (Mclean et al., 2004; Yu et al., 2006).

It has been demonstrated that female athletes land with a significantly lower flexion angle for the knee joint compared with male athletes (Hewett et al., 2006). Lower knee flexion angles have been reported at initial impact with female athletes who sustained ACL injuries than the others who did not (Hewett el al., 1996). Any changes in sagittal plane angles at the knee and hip joints could alter the loads on the ACL (Hewett et al., 2005).

Hewett et al. (1999) has illustrated the differences in sagittal plane hip torques between female athletes who had suffered an ACL injury and others who did not. Peak external hip flexion moments were higher in female athletes who had suffered an ACL injury compared to the other group who were uninjured female athletes (Hewett et al., 1999). High ground reaction forces at the lower limbs during landing has been documented in female athletes, which is as a result of the decreased use of the gluteus maximus to absorb the energy produced throughout a single leg landing (Alentorn-Geli et al., 2009).

There is strong evidence in the literature that valgus misalignment can increase the risk of non-contact ACL injury (Hewett et al., 2005). In addition, a correlation has been noticed between knee valgus angle and peak vertical ground reaction force (VGRF) in females who have had an ACL injury (Hewett et al., 2005).

1.6 Knee Valgus Angle and ACL Injuries

ACL injuries have been linked to knee valgus angles (Boden et al., 2009; Hewett et al., 2005; Renstrom et al., 2008; Krosshaug et al., 2007; Hewett et al., 2009). An increased risk of knee injuries may be as a result of peak knee valgus (Heitz et al., 1999; Ireland, 1999). Knee valgus has been considered one of the possible factors in non-contact ACL injury (Hewett et al., 2005), as knee valgus misalignment has been shown to be a common postural dysfunction in the lower extremities while performing weight bearing exercise, including SLS and SLHL. In this regard, SLS is often used by physiotherapists to assess the functioning of the lower extremities, as well as the neuromuscular control of the trunk (Beckman et al., 1989; Zeller et al., 2003).

The SLS is a dynamic movement which is necessary for a range of daily activities, making it ideal as a functional test (DiMattia et al., 2005). Examples of activities that include the action of SLS are climbing the stairs and running (requiring eccentric knee flexion in a weight-bearing position), although these activities are also more dynamic and so require additional muscle control. Zeller et al. (2003) hypothesised that if during SLS movement, increased knee valgus angle is observed, it may be even less controlled whilst performing other actions such as deceleration or landing. Moreover, performing closed kinetic chain (weight bearing) exercises such as SLS and leg presses means the lower extremities are fixed in relation to the ground, with movement at the knee joint enabled by movement at the hip and ankle joints in a controlled and conventional manner (Palmitier et al., 1991). Even so, if there is a lack of muscle strength and/ neuromuscular control, the knee may be placed in a dysfunctional position, such as knee valgus posture, during any exercise. Assessing the degree of knee valgus during sports movements will reveal the ability of the athlete to effectively control the lower extremity muscles in the frontal plane (Ford et al., 2003).

1.7 Non-biomechanical Risk Factors for Non-contact ACL Injury

A number of risk factors have been reported globally in the literature that may increase the chances of sustaining an ACL injury for both males and females. However, the main causes of these injuries can be split into two main categories: intrinsic (athlete-related) and extrinsic (environment-related) risk factors (Orchard, 2001). Intrinsic risk factors are age, gender, joint instability, limb asymmetry, previous injuries, as well as psychological stress under different levels of competition (Inklaar, 1994). Different field conditions, footwear and rules of the sport are considered to be extrinsic risk factors (Dvorak and Junge, 2000). The intrinsic factors in Bahr and Holme's (2003) study include age, sex, weight, strength, and the flexibility of the athlete, and extrinsic factors are the sporting surface, training methods used, equipment (i.e. footwear and padding) and weather.

1.7.1 Intrinsic Risk Factors

1.7.1.1 Gender

Many studies have stated that female players suffer a much higher incidence of injuries than men, especially non-contact ACL injuries (Murphy et al., 2003). There are many factors that might explain this, including anatomical structure and hormonal variations. Anatomical structural differences in women compared to men, include a narrow intercondylar notch and difference in ACL size (Rizzo et al., 2001). In addition, the differences in morphology between males and females have been well reported, which include differences in Q angle, pelvic shape/size, femoral notch width (Scovill et al., 2001), thigh length (Beynnon et al., 2001), overall laxity, and excessive foot pronation (Hewett et al., 2005). Although these factors may be seen as risk factors which can contribute towards an ACL injury, they nonetheless are considered to be non-modifiable by nature (Myer et al., 2005).

With regards to hormonal variations, despite scientific reports of estrogen receptors’ place in human ACL, it is debatable whether and how hormones affect ACL structure and composition (Wojtys et al., 2002). The results stated by some studies indicate that there is a higher risk of having ACL injury during the pre-ovulatory phase (Arendt et al., 2001), the time of maximum estrogen levels, when estrogen has been reported to reduce ACL strength by minimising the tensile properties of the ligament (Boden et al., 2010). Additionally, estrogen has been documented to have an influence on the central nervous system (CNS), which may lead to a decrease in motor skills in the pre-ovulatory phase (Wentorf et al., 2006). Moreover, the levels of women's hormones (i.e. progesterone, estrogen and relaxin) have been reported to change with their menstrual cycle, and have also been documented as increasing ligamentous laxity and reducing neuromuscular performance, which might reduce both passive and active knee stability in female athletes (Hewett, 2000). Furthermore, regarding knee positioning, it has been reported that, during landing, the knee joint becomes more extended in females than in males (Harner and Rhin, 2003). Despite the knowledge that female athletes might be more at risk of ACL injuries than males, the relationship between gender and other factors of lower-limb injury is still unclear (Murphy et al., 2003).

1.7.1.2 Previous Injury and Incomplete Rehabilitation

An incomplete rehabilitation programme, or poor rehabilitation after injury, is stated in many studies as a high risk factor for repeat injury of the same type and in a specific location. It has been found that there is a high risk of repeat injury for athletes who are not physically able to return to a pre-injury level of competition (Ekstrand and Gillquist, 1983). Additionally, a similar study reports that an insufficient rehabilitation programme is considered a risk factor for soccer players' injuries (Chomiak et al., 2000).

1.7.1.3 Psychological Factors

According to Coddington and Troxell (1980), an athlete's mental or emotional state might increase the chance of being injured. In addition, the effect of psychological factors is described in Andersen and Williams' (1988) study, which involved developing a model based on stress theory and injury. Some of the key areas of stress described by athletes are the fear of failure; worrying about the views of others such as fans, and more importantly, the coach; being unprepared to perform, and losing internal control over the environment (Hardy, 1992). Many studies have explained that stress plays a significant role in a player's performance. It has been shown that emotional stress results in an increase in blood flow (Wilkins and Eichna, 1941), believed to be a result of the release of adrenaline (Golenhofen and Hildebrandt, 1957), which has many effects on muscle contraction. According to Marsden and Meadows (1970), an increase in adrenaline during physiological activity alters muscle contractions evoked by nerve stimulation; adrenaline also decreases the duration of the slow twitch phase in the calf muscles, and that also affects muscles by stimulating β-adrenotropic receptors, as these are abolished by the β-adrenotropic antagonist DL-propranolol, and are copied by isoprenaline. Thus, all of these factors might contribute directly to the incidence of any kind of injury.

1.7.2 Extrinsic Risk Factors

1.7.2.1 Footwear and Padding

Protective equipment like shin pads and suitable footwear was made compulsory by International Federation of Association Football (FIFA) regulations, for both competition and training, in 1990 (McGrath and Ozanne-Smith, 1997). Compared to other designs, wearing edge-style cleats to play football could increase the likelihood of suffering an ACL injury; therefore, one study explored whether there is a link between cleat design and the occurrence of ACL tears among 3,119 American football athletes studying in high school and playing on natural turf (Murphy et al., 2003). Murphy et al. (2003) found that athletes wearing edge cleat designs with longer irregular cleats located along the periphery of the shoe, as well as smaller pointed cleats located internally, suffer from a significantly higher number of ACL tears, compared to athletes wearing other cleat types, which include screw-in, and pivot disk designs.

1.7.2.2 Playing Surface

Football is played on a rectangular pitch about 68m wide and 105m long, usually a grass surface, but occasionally on a surface made of artificial turf, sand or gravel. A player covers approximately 10 km. per game, of which 8-18% is at highest personal speed, and withstands significant impact forces of two to three times their individual body weight (McGrath and Ozanne-Smith, 1997). Thus, the surface and the environment surrounding the player are significant factors to consider when analysing the nature and incidence of soccer injuries (McGrath and Ozanne-Smith, 1997).

According to Murphy et al. (2003), playing soccer on artificial turf will increase the incidence of knee and ankle injuries. The same study reported that Tartan Turf has the highest incidence of injury, followed by Super Turf, then Astro Turf. That many more injuries are seen on artificial turf compared to other surfaces, may be because of its stiffness, as that may increase the friction force on the shoe. The stiffness of a surface can affect impact forces and that might result in the overloading of tissue, such as bone, muscle, cartilage, tendons and ligaments. Normally, friction is needed for rapid starting, cutting, stopping and pivoting, which are inherent in sports like football. However, increased friction forces may lead to an increased incidence of injury among players who play on artificial turf (Murphy et al., 2003).

1.7.2.3 Temperature

An increase in temperature can be expected to correlate with sweat loss, thus increasing the risk of dehydration. The differences in the amount of sweat loss in players are likely to have a direct relationship between dehydration and muscle fatigue during a match (Shirrefts et al., 2006). It has been found that there is a strong relationship between hot and/or sunny weather conditions and the rate of injuries that occur to the knee and ankle joints (Azubuike and Okojie, 2009).

1.7.2.4 Rules

The rate of severe injuries may be influenced by the violation of game rules, and that might be seen as a significant factor if game referees do not enforce the rules correctly. According to Chomiak et al. (2000), in a study of 398 players followed for up to one year, 25% of contact injuries occurred without foul play. Therefore, perceptions of fair play and continuous learning of techniques and skills may reduce the incidence of knee injuries (Peterson et al., 2000).

1.8 Neuromuscular Risk Factors for Non-contact ACL Injury

There is evidence that poor or abnormal neuromuscular control of the lower extremity biomechanics, especially at the knee joint, during any sport activity is a main contributor to non-contact ACL injury, especially in females (Hewett el al., 1996; 1999; 2005). Neuromuscular control is a combination of muscle strength, power, and muscular recruitment patterns that minimise knee joint loads (Myer et al., 2004). Despite the fact that multiple factors might underline the differences in the risk of having an ACL injury among males and females, neuromuscular control can be considered one of the important factors (Myer et al., 2004). Females may demonstrate one or more neuromuscular differences that increase loads over lower limb joints, especially the knee joints, during sporting activities (Hewett et al., 2001).

It has also been reported that the passive ligament structure to point of failure could be stressed by decreased neuromuscular control of the lower limb joints (Li et al., 1999). It has been reported that high levels of neuromuscular control are important to maintain dynamic knee stability (Li et al., 1999; Besier et al., 2001). Neuromuscular imbalance may be the main factor contributing towards ACL injury, which can happen under conditions of high loading activities of the knee joint during a dynamic situation, with incomplete active muscular restraint to compensate and reduce joint loads (Beynnon and Fleming, 1998). Gender related neuromuscular differences have mainly been detected in female athletes (Hewett et al., 2005). Neuromuscular imbalance in female athletes is reported to have been seen in ligament dominance, quadriceps dominance, and leg dominance (Hewett et al., 2005).

Ligament dominance happens when the ground reaction force (GRF) is absorbed by the knee joint ligaments rather than by the lower limb muscles when practicing sports manoeuvres (Hewett et al., 2002). This situation can result in high GRF and high knee valgus moments mainly when landing with a single leg, and during deceleration and rotating manoeuvres, making them potential danger mechanisms for ACL injuries (Ford et al., 2003; Myer et al., 2002; Hewett et al., 1996). Peak valgus moments are not just a result of external moments in the knee joint, but are also influenced by external moments of the hip and ankle joints (Winter et al., 1990). Therefore, lack of control concerning lower limb muscle coordination might lead to irrevocable loads on the knee, and this may put the ACL in a position of no return (Ireland, 2002).

Quadriceps dominance, which reflects differences between the quadriceps and hamstrings recruitment patterns, may be more prevalent in females (Myer et al., 2004). It has been reported that female athletes mainly use their quadriceps muscles in response to forward translation of the tibia, in contrast to male athletes who used their hamstrings more to stabilise anterior tibial displacement (Malinzak et al., 2001). This early activation of the quadriceps or late activation of the hamstrings, within a weight bearing stance, could be seen as being responsible for the lower extremities, resulting in landing with an almost straight knee during various sports tasks (Shultz et al., 2001). Therefore, it has been reported that landing with a nearly fully extended knee might be seen as a common risk factor for ACL injuries (Boden et al., 2000).

Another neuromuscular imbalance demonstrated by female athletes is leg dominance; this can be seen as a result of differences in muscle strength and joint kinematics between the lower limbs (Myer et al., 2004). Leg dominance (side to side) differences in muscular flexibility, strength, and coordination have been reported to be essential predictors for ACL injuries (Baumhauer et al., 1995; Hewett el al., 2005). Regarding leg dominance, Ford el al. (2003) found that female athletes had greater peak knee valgus angle when doing a box-drop vertical jump activity in comparison with male athletes.

Neuromuscular imbalances may not be the only factors that cause the gender disparity in ACL injury rates, but neuromuscular control may be seen as the highest cause of dynamic knee stability and offer the greatest potential for intervention (Griffin, 2001).

1.9 Prevention / Intervention for Non-contact ACL Injury

Several studies have reported that comprehensive interventions designed for female athletes would improve their overall neuromuscular control, and therefore, reduce the occurrence of ACL injuries (Hewett et al., 1996; Hewett et al., 1999; Mandelbaum et al., 2005; Gilchrist et al., 2008). The majority of intervention programs concentrate on neuromuscular and biomechanical risk factors (Yoo el al., 2010). This is because neuromuscular imbalance can be improved through appropriate training (Hewett et al., 2006).

Different prevention programs have been documented throughout the past two decades (Hewett et al., 1996, Caraffa et al., 1996; Hewett et al., 1999; Söderman et al., 2000; Heidt et al., 2000; Myklebust et al., 2003; Pfeiffer et al., 2006; Gilchrist et al., 2008; Steffen et al., 2008). They are based on different concepts and consist of different preventive training exercises such as strengthening, stretching, stability, plyometric, balancing, agility and endurance (Yoo et al., 2010, Hewett et al., 2006). However, the general effect of these exercise mechanisms on enhancing neuromuscular control, and minimising non-contact ACL injuries in female athletes, remains unclear (Alentorn-Geli et al., 2009).

The period of the training sessions varied from 10 to 90 minutes. In the study by Hewett et al. (1999) they used 90 minutes of training, and Heidt et al. (2000) used 60 minutes of implementing comprehensive procedures; however, this is too difficult to be applied during the season period. Interventions used by Söderman et al. (2000) ranged from 10 to 15 minutes; Myklebust el al. (2003) and Steffen el al. (2008) used 15 minutes; Pfeiffer et al. (2006), Mandelbaum et al. (2005), and Gilchrist et al. (2008) used 20 minutes. All of these reported interventions had a relatively short protocol that has the potential to be simply integrated into a regular season’s training program (Yoo et al., 2010). It has been suggested that long period protocols are difficult to conduct (Herrington and Munro, 2010).

Prevention programs that include high intensity training have been shown to have a better effect on minimising ACL injury or reducing overall biomechanical risk factors (Noyes et al., 2011). On the other hand, impractical procedures considered as too lengthy or expensive cannot be easily implemented (Hewett et al., 2006, Yoo et al., 2010).

Reported rates of training differed widely, from 100 % and 98 % stated in Heidt et al. (2000) and Mandelbaum et al. (2005) respectively, to 28 % reported in Myklebust et al. (2003). Steffen et al. (2008) conclude that the main reason for unsuccessful interventions (11 programs failed to minimise ACL occurrence) was due to the low compliance rate to training by the athletes and also the low volume of exercise intensity. Myklebust et al (2003) did not achieve a significant drop in ACL injury rates, and they reported a compliance influence in a sub-group only; the authors assumed this to be as a result of higher motivation within the sub-group.

One of the aims of the interventions is to minimise the occurrence of a non-contact ACL injury, but this usually needs a longer time and space commitment (Hewett et al., 1999; Hewett et al., 2006; Myklebust et al., 2003; Heidt et al., 2000; Söderman et al., 2000; Mandelbaum et al., 2005), which may deter athletes and their coaches from including the ACL injury prevention intervention programs in their training.

The existing intervention programs vary globally concerning the mechanisms of the programs, as well as the length and intensity of exercise (Noyes et al., 2011). The effect of these interventions in minimising the occurrence rate of non-contact ACL injuries vary. Therefore, further research is required to develop optimum programs to reduce non-contact ACL injury.

1.10 Hop Tests and other Physical Measurements

Many studies have examined the relationship between the measurements of hop tests and other physical impairments, such as muscle weakness (Barber et al., 1990; Noyes et al., 1991; Wilk et al., 1994; Greenberger and Paterno, 1995; Pincivero et al., 1997), or proprioception deficits of the knee joint (Katayama et al., 2004); while other studies have used hop tests with patients with knee injuries as indicators of functional performance capacity (Fitzgerald et al., 2001).

1.11 Importance of Hop Tests

As previously mentioned that an ACL injury can occur in a non-contact episode. The rate of ACL injuries is fairly high in sport activities that require performing tasks such as jumping and landing from a jump (Griffin et al., 2000). Therefore, need a better understanding of hop test performance (from the takeoff till landing) and the factors which might influence it. Hop tests are useful measures of physical performance and athletic function, and they can also be used to monitor progress, as well as recommend whether a return to sport or normal activity is likely to be beneficial or harmful for those recovering from a sporting injury or surgical intervention. Hop tests can combine and test the different elements that may have been affected due to an injury, for example joint stability, muscle strength and neuromuscular coordination.

Different hop test protocols have been described and utilised in the sport literature (Noyes et al., 1991; Booher et al., 1993; Fitzgerald et al., 2001; Phillips and van Deursen, 2008). These hop tests involve many protocols, such as a single-leg hop for distance, figure-of-eight hop, lateral hop, side hop, shuttle run, up-down hop, agility hop test and triple crossover hop for distance.

Landing from a jump is an essential part of most sports activities, and is always seen as a multi-joint movement that requires a large muscular effort from the muscles surrounding the ankle, knee and hip joints (Lees et al., 2004). As mentioned before, upon landing from a triple hop, the impact forces produced can reach a magnitude of up to twelve times the person’s body weight (Perttunen et al., 2000), which might result in lower extremity injury (Jacobs et al., 2007). To control joint flexion and decelerate the body when landing, large eccentric muscle forces exerted by the hip and knee extensors and ankle plantar flexors are required (McNitt-Gray, 1993).

During landing, a relationship between peak ground reaction force and the occurrence of many injuries such as ACL injuries has been noted (Hewett et al., 2005). Moreover, basketball, volleyball and adolescent football players with ACL injuries have a 20 percent greater peak GRF when compared to healthy subjects (Myer et al., 2005). This means that landing with a greater vertical ground reaction force may increase the risk of damage to the knee joint.

1.12 Landing Strategy

Landing with a large degree of knee flexion may reduce the magnitude of VGRF (Devita and Skelly, 1992). If landing strategies have been taught and demonstrated correctly to athletes, this will, potentially, have a significant effect on controlling and avoiding the occurrence of serious injury (Mandelbaum et al., 2005). When examining landings, it is important not to ignore the importance of gender (Salci et al., 2004; Ford et al., 2006), because differences in strategies and landing techniques have been noted in several research studies comparing males and females.

Many studies have investigated the relationship between different landing techniques and the changes in the contribution of the lower extremity joints to energy absorption. Some of these studies have addressed jumping techniques (Bobbert et al., 1987), and some sport-specific jumps (Miller and Nissinen, 1987), whilst others have reported the effects of landing surfaces (Gross and Nelson, 1988). However, the use of different individual landing strategies to control and reduce larger forces has clearly been shown in many studies. Although there are differences in the individual strategies being used, the results suggest an increase in vertical forces with greater height and knee extension. Therefore, the need to examine compression, torque and shear, linked with different performance strategies, is suggested in many studies, advocating activation of the lower limb musculature in landing strategies (Dufek and Bates, 1990). To achieve a stable landing, good balance is required. Stability can be maintained by appropriate feedback from the proprioceptive receptors located inside the joints, which provide information to the CNS (Riemann and Lephart, 2002).

1.13 Sensorimotor System

The sensorimotor system can be described as a combination of the physiological systems of complex sensory and motor processes (Lephart et al., 2000). Body movement and position in space information are collected by the somatosensory, visual and vestibular systems. These systems relay sensory information to the CNS to be integrated at three different levels of motor control. These levels are the brainstem, the spinal cord and the higher brain centres in the cortex (Fitzpatrick and Day, 2004). All systems, such as the nervous and somatosensory system, contribute towards the body's overall ability to maintain balance during any activity. To maintain body balance through joint stability, the CNS needs to integrate different components of static and dynamic control systems. Static components mainly include joint capsules, cartilage, ligaments and bony articulation, whilst muscles and tendons crossing the joint are the dynamic components (Johansson and Sjolander, 1993; Riemann and Lephart, 2002). This controlling system mainly comprises two parts: firstly, the feedback control system, where sensory receptors recognise or identify any change; secondly, the feed forward control system, which provides protective actions first (Riemann and Lephart, 2002). Sensory receptors are sensory nerve endings that are responsible for responding to a stimulus in the external or internal environment of an organism, and work together to contribute to the sense of awareness and consciousness; they also assist in the subconscious reflexive control of movement. The main receptors that exist in the sensory system are: cutaneous receptors (Collins and Prochazka, 1996; Refshauge et al., 1998; Collins et al., 2005), muscle spindles (Goodwin et al., 1972; McCloskey et al., 1983; Winter et al., 2005; Westlake et al., 2007), golgi tendon organs (Chalmers, 2002; Gregory et al., 2002; Stanfield et al., 2008) and joint receptors (Ferrell et al., 1987; Proske et al., 1988; Sojka et al., 1989; Johansson et al., 1991, 2000; Kandel et al., 2000; Williams et al., 2001).

1.13.1 Cutaneous Receptors

Cutaneous receptors are located within the skin to identify mechanical deformations, which allows the perception and movement of body joints (Refshauge et al., 1998). Several research projects have concluded that cutaneous receptors have a direct role in proprioception (Collins and Prochazka, 1996; Refshauge et al., 1998). However, these studies used finger movement to confirm this. Another recent study has used both elbow and knee joints to provide evidence, stating that cutaneous receptors are connected to proprioception and may provide proprioceptive senses (Collins et al., 2005). This suggests that cutaneous afferents could have a significant role in standing balance control, seen as a sensory input to the CNS regarding body changes.

1.13.2 Muscle Spindles

Muscle spindles consist of a number of intrafusal muscle fibres. These spindles are influenced by changes in the muscle's length and velocity (Winter et al., 2005). Muscle spindle activity increases when the muscle is stretched, and decreases during the muscle's shortened phase (Westlake et al., 2007). The role of muscle spindles in proprioception was identified many years ago (Sherrington, 1906; Goodwin et al., 1972; McCloskey et al., 1983). These studies used different isolation techniques such as anesthetisation and nerve blocking. The results show that muscle spindles had the greatest effect on proprioception. Goodwin et al. (1972) utilised muscle tendon vibrations to influence the afferents of the main muscle spindle. This artificial stimulation pointed out strong illusions of movement and position at the joint. In a study by McCloskey et al. (1983), they found that the vibration of muscle tendons at high frequency influenced the primary endings of muscles spindles, with illusions of the sway area of the body, while lower frequencies and greater amplitude mostly stimulated the secondary endings, helping in stimulating the static position of the extremity. Fitzpatrick and colleagues (1994) evaluated the ability of normal participants to maintain a standing balance position whilst depending on proprioceptive data gathered from the leg muscle spindles, in a condition where vestibular and vision were excluded and sensory receptors from the ankles and feet were isolated by ischaemic anaesthesia throughout step by step isolation techniques. This study concluded that normal participants are able to stand in a stable manner when lower extremity muscle receptors are the only source of data available to control postural sway during the application of isolation techniques.

1.13.3 Golgi Tendon Organs

The other type of muscle receptor is known as the Golgi Tendon Organ (GTO). These receptors are found in the muscle-tendon junction. The main characteristics of these receptors are that they have a very low threshold and a high dynamic sensitivity, which can provide information about muscle tension or any change in tension during standing or any other activity (Stanfield and Germann, 2008). The impulse from GTO moves to the spinal cord, leading to spinal reflexes linked with the ascending information. These reflexes in the spinal cord are an autogenic inhibition which has control over the contracting force of the muscles (Stanfield and Germann, 2008). The idea of load protectors being the only role for the GTOs to control the muscle during over tension activity at an injurious level has been refuted by linking GTOs response over the full range of muscle force (Chalmers, 2002; Gregory et al., 2002).

1.13.4 Joint Receptors

Joint receptors include four types located in the joint capsule and ligaments; these are: Pacinian corpuscles, Ruffini endings, Golgi tendon organ-like endings, and free nerve endings (Johansson et al., 2000). The classification of these receptors is according to how they react to stimuli and also according to the following characteristics: (1) the joint report in which they are active (e.g. static, dynamic, or both), (2) the stimulus intensity at which they reflect their threshold for activation (high-threshold or low-threshold), and (3) whether they stay active with persistent stimuli (slowly adapting) or react quickly and then become quiet (rapidly adapting) (William et al., 2001). Ruffini endings are slow adapting and have a low threshold of detection for mechanical stress. However, they are sensitive to intra-articular pressure, position change, amplitude and the velocity of joint movement (Proske et al., 1988; Ferrell et al., 1987). The Pacinian corpuscles are quickly adapting, have little threshold for detecting mechanical stress, and are activated during changes in joint movement velocity (acceleration and deceleration). They are inactive throughout static positions and constant velocities, and are known as dynamic mechanoreceptors (Johansson et al., 2000). The Golgi tendon organ-like endings are slow adapting, detect mechanical stress at high thresholds, and are generally influenced when a joint is at an extreme range of motion (Kandel et al., 2000). The free nerve endings, which are generally distributed, are activated when there has been damage to the joint, leading to an inflammatory response (Johansson et al., 2000). The literature does not provide a clear explanation about the role of joint receptors in proprioception. Nevertheless, the main role of joint receptors in gamma motor neuron activation provides clearer information (Sojka et al., 1989; Johansson et al., 1991). During the increase of activation in gamma motor neurons, the activation of muscles will also increase. In addition, the sensitivity of muscle spindles will increase as result of the activated gamma motor neurons, and produce stiff muscles. A reduction in stiffness in both muscles and joints is seen as a result of damage to the joint receptors, which may result in an increase in joint laxity (Freeman and Wyke, 1967).

1.14 Role of Sensory Motor System in Balance

During static standing or body movement, the ankle joints must respond in an appropriate manner to maintain the body’s centre of mass within the limits of the base of support (Gatev et al., 1999). It has been suggested that the ankle joint strategy is the main strategy used to control balance during non-perturbed standing (Gatev et al., 1999). Therefore, in order to maintain and correct posture, the body relies on sensory information from the sensory receptors. The information received is then transmitted to the spinal cord to prompt reflexive changes to control the body's position or movement, or at the supra-spinal level for more specific corrections that may be required (Lalonde and Strazielle, 2007).

1.15 Proprioception

Proprioception has been described as a cumulative neural input to the CNS, which is obtained via information from the mechanoreceptors in the skin, joint capsules, tendons, surrounding muscles and ligaments (Wassinger et al., 2007; Delahunt, 2007). It has been described in early research that the total body posture and stability of the joints will be affected by the afferent information received from proprioceptors in the joints, tendons and muscles (Sherrington, 1906). Reductions in both proprioception sense and muscle strength can be seen as possible causes of ankle stability during the latter stages of ankle sprains (Willems et al., 2002). Therefore, it can be concluded that muscle weakness and proprioception might affect balance and the measurement of postural sway.

1.16 Assessment of Functional Performance

Within sport, the main objective of rehabilitation programmes is to return the athlete as quickly, efficiently and safely as possible back to full participation. There are several ways of determining the athlete's performance and ability. However, the only accurate way to achieve this is to perform a functional trial. Functional performance tests are frequently used to verify an athlete's participation status. These tests are effective and helpful because they involve multiple components, such as hop tests, balance and neuromuscular coordination, muscle strength, lower limbs force production, and knee kinematics, which can all be affected after injury. Researchers have utilised single and multiple leg hop tests due to the requirements of sports related functions. To investigate athletic stability and performance, single-leg hop and crossover hop tests have been used; these are regarded as challenging and specific to athletic performance (Colby et al., 1999; Ross et al., 2002; Ross and Guskiewicz, 2003; Brown et al., 2004; Wikstrom et al., 2004; Wikstrom et al., 2010; Munro and Herrington, 2011). Balance tests have been used to test the subject's ability in functional and static/dynamic situations (Blackburn et al., 2000; Hertel and Olmsted-Kramer, 2007; Phillips and van Deursen, 2008). Additionally, the assumption is often made that the muscle strength of the lower extremities is reflected in and affects hop test scores. A positive connection between isokinetic muscle strength and performance in single-leg hop and crossover hop tests has been revealed in the literature (Barber et al., 1990; Noyes et al., 1991; Wilk et al., 1994). In addition, muscular strength is usually seen one of the most important aspects of dynamic athletic performance, particularly if the sporting activity requires high force generation over a short period of time (Newton and Kraemer, 1994). In fact, knee-valgus angle in general, athletic, and injured populations has been evaluated using two-dimensional analysis (Willson et al., 2006; Noyes et al., 2005). Knee valgus angles have been associated with ACL injuries (Boden et al., 2009;

Hewett et al., 2005; Renstrom et al., 2008; Malinzak et al., 2001; Krosshaug et al., 2007; Hewett et al., 2009).

As mentioned above, all of these contributing factors have a direct effect on an individual's hop performance before or after an injury. Therefore, each of the individual factors will be discussed in the following paragraphs in depth.

1.16.1 Hop for Distance Test

Noyes et al. (1991) describe a single-leg hop for distance as one of the four hop tests that may be appropriate as an outcome measure to evaluate patients' performance during rehabilitation after ACL reconstruction. It has been stated that hopping tasks can be used as a tool to predict whether individuals are likely to have problems in the future (Fitzgerald et al., 2001), and also to evaluate recovery (Heckman et al., 2000; Gotlin and Huie, 2000).

Furthermore, athletes in many sports need to move and hop horizontally in a very fast and efficient manner, and so they usually follow training programs specifically tailored to improving their ability to move and hop horizontally (Ross et al., 2002). Noyes et al. (1991) have developed four single-leg hop tests to evaluate an athlete's horizontal movement skills effectively, including their horizontal hopping abilities. The four tests are: the single hop for distance test, the triple hop for distance test, the crossover hop for distance test and the six-metre (6-m) hop for time test.

Although single-leg horizontal hop tests are valuable in evaluating strength, power and kinaesthesia (Tippett and Voight, 1995; Decarlo and Sell, 1997), they are typically used to evaluate the progress of training exercises, or to assess the level of recovery after injury or surgery to the lower extremity in either field or clinical settings. Typically, single-leg horizontal hop testing has been applied at four to six week intervals (Worrell et al., 1993; DeCarlo et al., 1999; Unger and Wooden, 2000). The four single-leg hop tests that evaluate horizontal hopping abilities, the single hop for distance test, the triple hop for distance test, the crossover hop for distance test and the 6-m hop for time test, have been explained in detail by Ross et al. (2002) and Munro and Herrington, 2011 (see Figure 1.3).

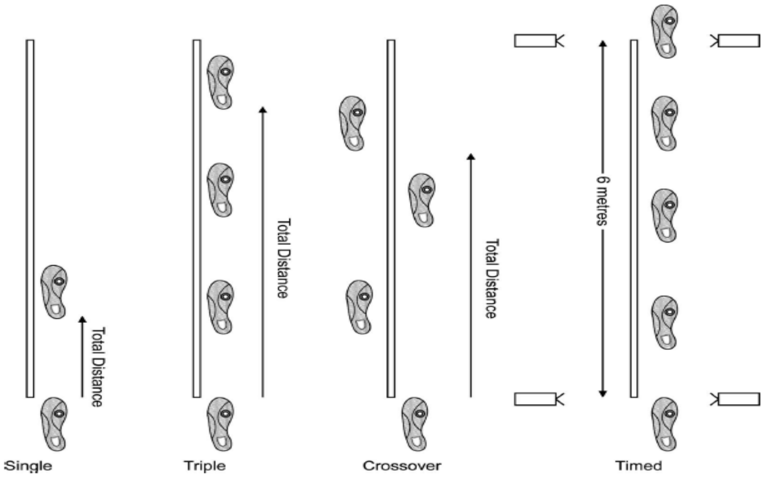


Figure 1.3. A figure of four single-leg hop tests procedure (Munro and Herrington, 2011)

Many studies have shown that these hop tests can identify differences between limbs in injured participants (Goh and Boyle, 1997; Petschnig et al., 1998; Reid et al., 2007). Therefore, they are generally used with injured participants to determine patient function. Hop tests are also used in healthy people to examine limb symmetry (distance and height of the hop) and predict overall lower limb strength and power (Hamilton et al., 2008).

1.16.1.1 Hop Test Reliability

Single-leg horizontal hop tests have demonstrated acceptable reliability when the interval between test-retest sessions has been two days or less (Booher et al., 1993; Bolgla and Keskula, 1997). However, the test-retest intervals used in previous studies do not replicate a clinical setting, as test-retest sessions are usually separated by four to six weeks (Worrell et al., 1993; DeCarlo et al., 1999; Unger and Wooden, 2000). The time that separates test-retest sessions may affect reliability (Currier, 1990; Ross, 1997), therefore, it is necessary to evaluate the single-leg horizontal hop and crossover hop tests’ reliability, with time intervals between testing sessions that more closely replicate the time frames that may be used in a clinical setting (Ross, 1997). It has been demonstrated by Munro and Herrington (2011) that one week time interval between testing sessions would be more closely replicate the time frames that may be used in a clinical setting.

Between-session hop test reliability in 22 recreational athletes was investigated by Munro and Herrington (2011) using four hop tests, the single hop for distance, triple hop for distance, 6-m timed hop and crossover hop for distance tests, and they found that the ICC for the hop tests ranged between 0.76 and 0.92 with learning affects were present in all tests. Learning affects findings in all participants (male and female) for the single and triple hop for distance tests were three trials to achieve before stabilised scores, whereas crossover hop test scores stabilised after four trials for all participants, and the timed hop stabilised after four trials in women and three in men. Additionally, hop test reliability in both injured and uninjured participants has been demonstrated to be high (Booher et al., 1993; Bandy et al., 1994; Paterno and Greenberger, 1996; Bolgla and Keskula, 1997; Ageberg et al., 1998; Hopper et al., 2002; Ross et al., 2002; Reid et al., 2007). However, only two of these studies provide information about the subjects' activity levels (Ageberg et al., 1998; Ross et al., 2002). This is an important point because results from an athletic group cannot be generalisable to sedentary people and vice versa. In addition, studies usually use an unequal number of men and women (Booher et al., 1993; Bolgla and Keskula, 1997; Ageberg et al., 1998; Hopper et al., 2002; Reid et al., 2007). Moreover, in some studies, the authors have stated that learning affects were present (Booher et al., 1993; Bolgla and Keskula, 1997; Ageberg et al., 1998; Hopper et al., 2002; Reid et al., 2007), which may have confounded the reliability values of these studies. Although learning affects were only reported by Bolgla and Keskula (1997), they adequately investigated differences between trials and reported that three practice trials were sufficient for the crossover, triple, and timed hops, while four trials may be required for the single hop. This study concludes that further examination of the learning affects associated with hop tests is needed.

Furthermore, ICCs have been reported for hop tests in patients following ACL reconstruction, with an ICC of 0.76–0.97 for a single hop in a distance test (Kramer et al., 1992; Paterno and Greenberger, 1996; Brosky et al., 1999; Reid et al., 2007). The reliability of three single-leg hop tests was examined by Booher et al. (1993) using 18 healthy participants, with tests consisting of a hop distance, a 6-m hop for time, and a 30-m agility hop. ICCs ranged between 0.77 and 0.99. The test-retest reliability of four single-leg horizontal hop tests has also been established in 18 healthy subjects; Ross et al. (2002) investigated a single-leg hop for distance, with a time interval of about four weeks between two testing sessions. This study indicated excellent reliability (ICC's 0.92-0.97) for the four single-leg hop tests.

Different hop tests have also been evaluated (Reid et al., 2007) for patients following ACL reconstruction as performance based outcome measures, reporting ICCs of between 0.82 and 0.93. The single-leg hop test has been reported to have the highest reliability value when patients are involved in several tests, such as a single hop for distance, a triple hop for distance, a 6-m timed hop and crossover hops for distance, over four repeated test occasions over a six week period. Because of the high functional demands during sporting activities, it would seem reasonable to use hop tests to observe and evaluate any changes in an athlete's condition.

1.16.2 Assessment of Balance

Balance testing has become an important outcome measurement in sports rehabilitation and is well documented with researchers focusing on developing both clinical and laboratory measures for the identification of deficits following injury.

There are several ways of testing for balance using both static and dynamic techniques. One of the most commonly used tools in a laboratory setting to measure balance and GRFs for the calculation of intersegmental forces and moments, is the force plate (Corazza and Andriacchi, 2008). Force plate output has progressed to the point of being able to measure postural stability. The most variable force plate output is the centre of pressure (COP) (Lafond et al., 2004); define this as the point of application of the GRF (van Deursen and Everett, 2005). Different studies by different authors have utilised COP to determine the balance of participants (Evans et al., 2004; Ross et al., 2009). During the standing phase, with both feet in contact with the ground, the location of COP is inside the base of support and the stability limit, as shown in Figure 1.4 (van Deursen and Everett, 2005). During balance tests, COP displacement can be used as a reference for postural control (Lafond et al., 2004). A number of parameters can be utilized to represent these changes, including COP parameters such as velocity, mean area, length, excursion and sway area (Lafond et al., 2004; Bauer et al., 2008; Lin et al., 2008). COP excursion can be explained as the total distance between each COP position over the testing time (Ross et al., 2009).

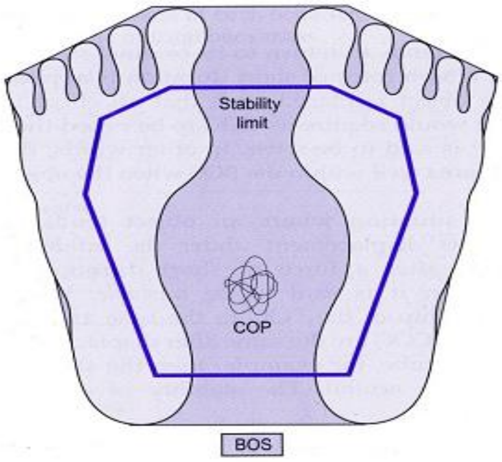


Figure 1.4. Illustrates the site of COP (van Deursen and Everett, 2005)

However, to maintain balance and a calm stance over a period of time, COP may fail to determine postural stability deficiencies, as it does not represent actual person activity. Therefore, a dynamic balance test was developed by Riemann and his colleagues (1999) who developed a dynamic measure clinically, by evaluating postural control throughout a functional performance trial. In addition, the TTS has been used as a method for assessing a person in a dynamic condition, in combination with a functional hop protocol using a force platform (Ross et al., 2009).

The duration of tasks performed when applying static and dynamic balance tests has also been considered a debatable point between studies. During static stance, duration has been measured through different trial durations, ranging from five to 60 seconds (Goldie et al., 1989; Goldie et al., 1992; Palmieri et al., 2003), and from three to 20 seconds during jump landing activities (Colby et al., 1999; Ross and Guskiewicz, 2003; Wikstrom et al., 2004). Consequently, it has been suggested that the shortest sampling interval (3 seconds) is close enough to represent athletic performance during a balance test (Wikstrom et al., 2005b).

1.16.2.1 Balance Assessment Reliability

The force platform used in balance tests is, like any other measurement tool, subject to measurement errors. These consist of three types of variability: intra-session (on the same testing day), inter-rater (between raters or experimenters) and inter-session retest (between different testing days) (Bauer et al., 2008). However, there is agreement in the literature that using a force plate is a reliable form of measurement for both COP and TTS parameters (Birmingham, 2000; Ross et al., 2005).

The reliability of COP measurements has been widely investigated using different protocols and parameters. Birmingham (2000) found moderate to excellent reliability values with ICC ranging between 0.41 and 0.91. Birmingham (2000) measured the total length of the COP path throughout three repetitions under four different testing conditions. Similarly, four testing conditions have been used in another study by Bauer et al. (2008), who illustrate the influence of the visual dimension on the reliability of examining COP and reported better reliability in tasks with closed eyes rather than open eyes. However, all COP variables (mean area, length, medial/lateral and anterior/posterior sway) found good to excellent reliability values. Lafond et al. (2004) and Lin et al. (2008) used the same participant group with the same testing situations and reported good reliability for COP parameters, which include COP mean velocity, sway area, COP range, mean power frequency (MPF), and root mean square distance.

The TTS has also been utilised to examine stability when completing functional hop procedures. TTS' measurement reliability has been reported in several studies; ICC values of 0.79 for anterior/posterior and 0.65 for medial/lateral TTS have been reported (Ross et al., 2005). The subjects in this study were required to maintain a single-leg position for 20 seconds, and the study concluded that TTS represents a reliable parameter for evaluating postural control.

1.16.2.2 Static Balance Test

Stability during single-leg stance is completed throughout corrective movements, and during reflexive contractions of the muscles in the ankle joint (Freeman et al., 1965). Testing of postural control has attracted widespread attention in the field of sport rehabilitation since the work of Freeman (1965). Researchers have used tools such as force plates to determine postural deficits (Hertel and Olmsted-Kramer, 2007; Ross and Guskiewicz, 2004; Brown et al., 2004). Numerous researchers have directly examined postural control following sports injuries (Evans et al., 2004; Leanderson et al., 1996; Ross and Guskiewicz, 2004; Perrin et al., 1997; Hertel and Olmsted-Kramer, 2007). Most of these studies used the static-leg stance balance under both eyes open and closed conditions. Single-leg balance test using a force plate has been utilised to examine static postural stability, or to measure the ability to minimise large excursions of the COP. Evans et al. (2004) measured COP excursion velocity during single-leg stance with eyes open in 15-second trials. The authors collected athlete participants in a prospective study; the participants were evaluated one, seven, 14, 21, and 28 days after acute unilateral ankle sprain, to compare with the data collected before having the injury. They found that both the injured and non-injured ankles showed deficits the day after injury. However, the non-injured ankle returned to baseline measures by day seven, while the injured ankle did not recover until day 14. Leanderson et al. (1996) carried out another prospective study of postural stability in single-leg stance. They recruited 53 ballet dancers for their initial evaluation. Only six dancers had an ankle sprain during the study. The injured group demonstrated a larger mean sway and sway area on the injured leg the day after the injury than before the injury. Other researchers used different parameters to evaluate the effects of recurrent sprains using force plates throughout single-leg stance. Ross and Guskiewicz (2004) examined Medial-Lateral (M-L) and Anterior-Posterior (A-P) sway separately in 14 healthy participants, and 14 participants with functional ankle instability, while standing with eyes open for 20 seconds for three trials on one leg. There was no difference in mean sway between groups in the AP ($p = 0.28$) and ML ($p = 0.65$) directions. Perrin et al. (1997) used basketball players with one or more ankle sprains, and healthy participants, to study postural sway during bilateral stance. A greater area of sway was demonstrated in the participants with an ankle sprain under both conditions of eyes open and closed. In addition, a positive relationship has been found between the area of sway and the number of ankle sprain injuries sustained. However, it is very difficult to evaluate static or dynamic balance in the ACL injured group directly after knee injury because of the severity of pain and difficulty in determining the ACL rupture directly after an injury, which requires screening such as Magnetic Resonance Imaging (MRI) to confirm the diagnosis.

1.16.2.3 Dynamic Balance Test

During athletic participation in many activities, dynamic conditions can be seen as more sensitive to the motor-control deficits associated with balance performance in active individuals. Therefore, it has been suggested that static single leg balance (SLB) tests might not be enough to evaluate balance performance. Several tests have been developed/used to examine dynamic postural control (Colby et al., 1999; Phillips and van Deursen, 2008; Ross et al., 2008; Ross et al., 2009). TTS using a force plate has been reported as being a successful method for determining the amount of dynamic postural control, in order to calculate how fast subjects stabilise, in combination with a functional hop protocol. TTS can be defined as the time needed to reduce the difference between the smoothed GRF and the range of vibration of a matching part of the GRF in a stabilised single-leg of participants (Ross et al., 2009), as explained in Figure 1.5.

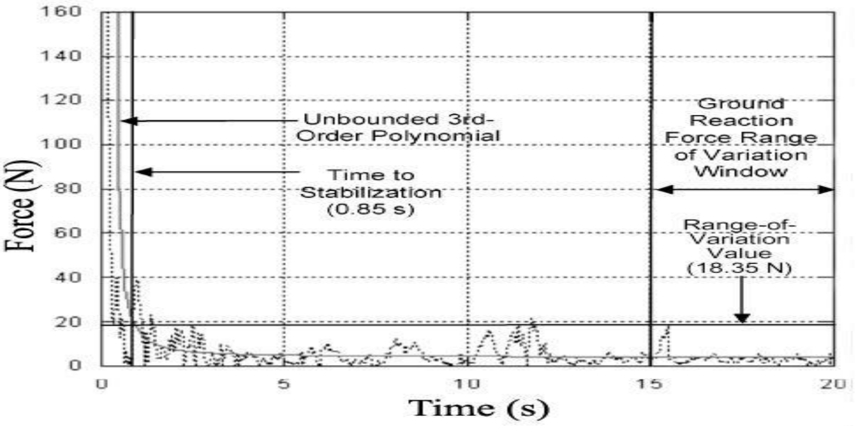


Figure 1.5. TTS measurement:

The window (of the GRF ranging from 10–15 seconds) is used as an example to measure the range of variation. The bold horizontal black line stands for the range of the variation line of 7.96 N. TTS was 1.63 seconds, which is the time at which the unbounded third-order polynomial crossed the range of variation line (Ross et al., 2005).

Different reasons have been given for using TTS. Some authors have utilised it to evaluate the effects of fatigue (Wikstrom et al., 2004), showing the variations among healthy participants and other participants with reconstructed ACL (Colby et al., 1999; Phillips and van Deursen, 2008), or in patients with unstable ankles during functional activities (Ross et al., 2008). In these studies, two procedures were followed to evaluate TTS: a step down from a raised platform or a hop and land onto a force platform. In the hop procedure, the participant can either jump in a vertical direction or hop in a horizontal forward direction. Both need the distance or minimum height to be adjusted for each participant. To determine which landing procedure would be more appropriate to establish which deficits are present in participants with functional ankle instability, during the single-leg hop landing, the authors asked the participants to hop to half of their maximum hop height and land on one leg on the force plate. However, it would have been more appropriate if they had used 80 per cent of maximum hop height, as 50 per cent may have been very easy to achieve for some participants. Wikstrom et al. (2005a) recruited 58 subjects who performed either a step down or a jump procedure. Both healthy and functional ankle instability participants were used to determine which procedure was more efficient at establishing deficits using TTS. The step down procedure used the test leg as the step down leg from a 20-cm-high platform onto a force plate, which was similar to the procedure used by Colby et al. (1999) when investigating subjects with ACL deficits. The jump landing procedure required each participant to stand at a distance of 70 cm from the force plate and jump onto a designated marker placed at a point equal to 50 per cent of the participant's maximum vertical jump. However, the jump procedure reported greater TTS scores (2381.7 ± 36.5 ms) in the vertical direction than the step procedure (1533.5 ± 71.8 ms). This highlights that the jump procedure is more effective in identifying TTS variations between healthy and functional ankle instability groups. The maximum horizontal hop distance has been used by other authors, for example Phillips and van Deursen (2008). They recruited 60 participants, 30 with ACL deficiency (ACLD) and 30 healthy subjects, to compare variations in stability. They used TTS to evaluate stability following landing from a hop activity, while each trial was applied using maximum horizontal hop distance, they found differences between both groups.

1.16.2.4 Learning Effect

The learning effect can be explained as the improvement in sensorimotor representations within the CNS, which can be as a result of the raised effectiveness of the CNS in planning and controlling highly practised activities (Ivens and Marteniuk, 1997). However, it has been observed during balance tests that repetitive exposure allows for a learning effect within a task and over time (Goldie et al., 1992; Hertel et al., 2000). A large number of trials, including Hertel and his colleagues (2000), have noted that six practice tasks are required before recording information about a star excursion balance test. However, there is a lack of clarity regarding whether participants should be allowed to practice in addition to the six trials. In another study (Wikstrom et al., 2005b), each participant was requested to complete three successful tasks on three different days. However, the researchers in this study did not account for or report the number of failed attempts. Another study used three practice tasks and three successful trials (Ross and Guskiewicz, 2004). Ross et al. (2005) performed three practice tasks and seven testing trials. Whilst in Brown et al. (2004) used four practice tasks and five test trials to assess functional ankle instability. As a result of the differences in the number of tasks performed within the studies reviewed, and since there is no standard procedure for practice and testing trials to reach stability in measurements, further practice and testing trials are required to avoid possible learning effects.

1.16.2.5 Balance Performance and Hop Tests

The relationship between balance performance tests and hop tests has not been widely investigated or explained in the literature. During a functional task, sensory and motor coordination of the lower extremity joints is required for balance. A number of studies have looked at postural stability at the end of a dynamic task (Colby et al., 1999; Ross and Guskiewicz, 2004; Wikstrom et al., 2004; Wikstrom et al., 2005a; Ross et al., 2008; Ross et al., 2009), reported as injury predictor (McGuine et al., 2000), and after ACLD (Phillips and van Deursen, 2008). These studies point to a relationship between balance performance variables and functional activities. Moreover, hop performance is also assumed to determine lower limb strength, power, and balance components in an athletic individual. In Phillips and van Deursen’s (2008) study, strong correlation was found between TTS utilising COP excursion (TTS-COP) and hop distance in the ACLD participants, but not in the healthy population. The authors suggest that ACLD participants may use other techniques to complete the task. The maximum forward single-leg hop test was performed to detect subjects' hop distance performance, and TTS after landing from a hop onto a force plate was also examined. A different hop performance test was used in the study by Hamilton et al. (2008) to evaluate the relationship between the subject’s performance in the triple hop distance test (THD) and hamstring strength, vertical jump height, and balance tests utilising the Balance Error Scoring System (BESS). Forty subjects were recruited in this study from soccer players (student athletes). This study concluded that the THD is not associated with the BESS test, although the participants in this study were asked to wear shoes for the THD test but not for the BESS, which may have created the possibility of error in comparing both tests.

In Birmingham’s (2000) study, the relationship between 30 healthy participants in the performance of forward single-leg hop for distance and single-leg standing balance using a force plate was investigated. The author utilised COP based on the mean of the three repetitions, under four complex progressive stability testing situations, as explained in the following: 1) standing with eyes open on a firm stable platform, 2) standing with eyes open on a foam mat positioned over the platform, 3) standing with eyes closed on the stable platform, and finally 4) landing with eyes open from a maximal single-leg forward hop. The results have been reported using Pearson correlation coefficients (*r*), and the test demonstrates a negative relationship between standing balance performance tests, and single leg forward hop distances ranged from - 0.37 to - 0.63. The greater relationships found were during the test done with eyes closed and after landing from a maximal single leg hop. Another study carried out by Tveter and Holm (2010) recruited healthy children (aged 7-12 years old) to investigate the influence of balance performance, muscle strength, gender, and age on hop distance in single leg hopping. This study reported a weak negative association between static balance test and hop distance. A static balance performance test was done by achieving 30 seconds of two trials on each leg using the KAT 2000; while hop distance was tested twice for each leg using the GAITRite system. Mean data from the balance and hop distance tests (for the two trials on each leg) was calculated, and the best score from each test was used in the data analysis. However, in their study no practice trials were carried out before each of the individual tests and this may invalid the final results because of the learning effect. Due to a lack of published papers investigating this association, and due to a myriad of balance tests used in the literature, the final conclusion of the relationship between hop test and balance performance is still difficult to explain and requires further investigation.

1.16.2.6 Muscle Strength and Balance Tests

Many studies have examined postural stability at the end of a dynamic task (Colby et al., 1999; Wikstrom et al., 2004; Ross and Guskiewicz, 2004; Wikstrom et al., 2005a; Ross et al., 2008; Ross et al., 2009). These studies suggest a correlation between the variables of functional ability and balance performance. However, hop tests are also supposed to test muscle strength, power and balance elements in an athletic individual. Although within this section the initial three papers reviewed are for a relatively younger population, the majority of papers within the literature are predominantly studies carried out on a middle aged and elderly population; these are explained in the following paragraphs.

Muehlbauer et al. (2012) examined the relationship between measures of isometric and dynamic muscle strength and variables of static and dynamic postural control in a middle-aged population. Thirty-two middle-aged healthy subjects performed static and dynamic balance tests, as well as maximum isometric and dynamic muscle strength tests, of the ankle plantar flexor muscles. This study found no correlations between measures of balance and strength value. However, in this study, many tests were performed, including static and dynamic balance tests, as well as isometric and dynamic muscle strength tests, which may have resulted in some fatigue. Although physical fatigue was to some degree controlled during both tests by including what was thought to be a sufficient rest interval between each trial, there might have been some mental fatigue, including loss of focus and concentration during the tests. However, overall, despite its limitations, this is a robust study; therefore, the results can be accepted.

Yu and Lee (2012) investigated the effects of a core stability training programme lasting eight weeks on lower extremity muscle strength and postural stability. Forty healthy subjects were randomly allocated to one of two groups- a core stability training group (CST) including 20 subjects, and a control group of 20 subjects. The CST group had three 60-minute core stability training sessions per week for eight weeks, whereas the control group did not have any training sessions. The measures were taken pre- and post-training and were of lower extremity muscle strength and postural stability. This study found a relationship between lower extremity muscle strength and balance in the CST group. However, none of the parameters significantly improved in the control group. In addition, differences were found between lower extremity muscle strength and balance between the CST group and the control group after completing the training programme. These results reveal that the CST programme enhanced motor performance skills by increasing lower limb muscle strength and improving postural stability, and, potentially, this has clinical relevance as it may prevent musculoskeletal disorders. One of the strengths of this study is that it was a randomised study with a true control group, that is, they did not do any training. However, what is not clear is whether the subjects were told not to partake in any physical activity, which could have influenced the results. However, although differences were noted, there were no power calculations, which would have strengthened the study.

Ringsberg et al. (1999) investigated the relationship between clinical tests of balance, gait and muscular strength in 230 elderly women (mean age 75 years). Balance was tested using single-leg standing (the time was recorded until balance was lost); however, it is not clear how this was determined or if a Chattecx computerised balance system was used. Isometric muscle strength (knee flexion, extension and ankle plantar flexion) was investigated using a Biodex computerised dynamometer. The time and number of steps taken to walk a specific distance were measured. The results demonstrate no relationship between the computerised balance tests and all the other tests performed, although there was a moderate relationship in a non-computerised balance test between gait time (r = -0.50) and number of steps (r = -0.40), this study included 230 elderly women who were chosen randomly, the authors have not mentioned which specific randomisation system was used, and that may have led to bias.

Wolfson et al. (1995) evaluated the effect of lower limb strength, gait and balance on the rate of falls in nursing home residents. Knee and ankle dorsiflexor muscle strength and balance (EquiTest balance platform) were tested in community resident participants. There was a moderate correlation between loss of balance during the sensory organisation test and diminished lower extremity strength, and also the same correlation between ankle dorsi- and plantar-flexion moments. This study concluded that there was a strong correlation between lower extremity strength, balance and gait.

1.16.3 The Role of Muscle Strength in Landing

The importance of muscle strength in landing manoeuvres has been stated in many studies. Jacobs and Mattacola (2005) report that women with greater eccentric hip-abductor peak torque demonstrated lower peak knee-valgus angles during landing, therefore potentially reducing the stress on the ACL. This study concluded that increasing eccentric hip-abductor strength might improve knee-joint kinematics when landing from a hop. However, in this study eccentric peak torque data were collected using Biodex System 3. Eccentric muscle testing consisted of two sets of five repetitions, one practice set and one test set. Nonetheless, one test set may not be enough to determine the peak torque value. If three test sets are obtained, this might be more appropriate as the peak value can be chosen from the set.

Sell et al. (2010) evaluated the effects of extra equipment weight on the knee joint kinematics and vertical GRF’s of two-legged landing in soldiers. They found with the additional weight of equipment that maximum vertical ground reaction forces, maximum knee flexion angles, and the time from initial contact to these maximum values all increased. They concluded that eccentric strengthening of the knees and hips should be incorporated into soldiers' training programmes to induce musculoskeletal and biomechanical adaptations to minimise the risk of musculoskeletal injury during two-legged landing manoeuvres. They stated that correct landing techniques should be learnt by soldiers during landing training; however, there is no specific definition of what constitutes a correct landing technique. Therefore, no specific landing techniques are taught during training. In addition, within this study, the authors evaluated the effect of additional weight on landing, and stated that the authors themselves performed the tests with and without the equipment that soldiers would carry. However, they did not explain the phrase "additional weight" and it was not clear how many kilograms the soldiers' equipment weighed.

Kim and Tan (2008) evaluated the strength of the thigh muscles and GRF when landing from vertical jumps. Their conclusion was that the combined torque of eccentric quadriceps and hamstring muscles at speeds of 60 deg/s is the most significant determinant of VGRF ($p < .05$); also, combined eccentric torque as well as VGRF are inversely related to the time to peak ground reaction force for the three jumping heights ($p < .05$).

Yeow et al. (2009) investigated the effect of landing height on energy dissipation in the lower extremity joints. The authors found that the hip and knee joints delivered much greater joint power and did more eccentric work than the ankle joints at both landing heights. Additionally, a large increase in eccentric work was reported at the hip joint in response to increasing jump height. However, a double-leg landing technique was used in this study, and these results cannot be generalised to performing landing on a single-leg. In addition, the authors used two different types of force plates in their study, which may account for some inconsistencies in the data. Preferably, a single type of force platform should be used for all data collection as every tool has its own different sensors, and therefore this may affect the results. Therefore, from the aforementioned studies, it can be concluded that the eccentric strength of the lower extremity muscles is an important element during the landing phase.

1.16.3.1 Muscle Strength and Hop Tests

Muscular strength in the lower extremities is usually seen as a reflection of, and as affecting, hop test scores. The literature suggests that there is a positive relationship between isokinetic muscle strength and performance for single-leg hop and crossover hop tests (Barber et al., 1990; Noyes et al., 1991; Wilk et al., 1994). A relationship has been illustrated by Barber et al. (1990) in their research carried out with healthy and ACLD participants using an isokinetic test (Cybex). They found that for a single-leg hop test for distance 12 out of 18 ACLD participants who reported suffering from quadriceps muscle weakness had abnormal scores. Whilst hop tests are reliable functional tests, particularly when it comes to weight-bearing activities, some participants may not be capable of taking such tests after an injury. In fact, it has been found that 40 percent of those who were not able to return to normal activity, would not perform or complete the hop tests for time and distance, due to fears of the injury or pain would re-occurring (Rudolph et al., 2000).

Several field tests are required to examine participants who may not be able to complete a recommended test, or who may perform below their ability as a result of fear of the test protocol (McCurdy et al., 2004). Due to fearfulness following an ACL injury, not all patients may be confident in doing this test, and so other test procedures may need to be considered. Therefore, Barber et al. (1990) could have considered that other reliable and valid unilateral tests may be required after ACL injury, as well as unilateral hop tests, to evaluate deficiencies. Other tests such as a bilateral squat test (Blazevich et al., 2002), have high reliability measures: $r = 0.98$ and $r = 0.97$, respectively, for isometric bilateral squats with a shoulder width stance. However, it has to be recognised that these tests are not as challenging as unilateral test conditions and may therefore not be sensitive enough to detect deficits in participants. A further weakness is that Barber et al. (1990) did not state a statistically significant correlation between the 60°/sec quadriceps muscle percentage deficit scores and abnormal symmetry scores for a single-leg hop for distance in subjects with ACL deficiency.

Noyes et al. (1991) reported a moderate relationship between muscle strength measures and hop tests. Sixty-seven participants (40 males and 27 females) demonstrated a moderate correlation between both quadriceps and hamstring muscle strength and single-leg hop tests. However, in this study, where bilateral variations were analysed via hop and jump tests, kinetic variables such as forces, impulse and power, were not measured.

Wilk et al. (1994) also noted a strong correlation between isokinetic muscle testing and three single-leg hop tests. The participants performed isokinetic strength testing on a Biodex dynamometer at three speeds, 180, 300 and 450 degrees/sec., for quadriceps and hamstring muscles. In addition, one-legged functional tests were examined as timed hops, hops for distance and crossover triple hops. It was concluded that a positive relationship exists between quadriceps muscle strength at speeds of 180 and 300 degrees/sec. and the three hop tests. This study was conducted on 50 ACLR patients and the researchers noted appropriate inclusion and exclusion criteria; however, a weakness was that the inclusion criteria did not specify which type of ACL reconstruction surgery these subjects had had, whether bone-patellar tendon-bone or semitendinosus-hamstring graft. The type of graft may have an influence on function, and it would have been preferable to use a single graft type to give more accurate results. However, it is acknowledged that a major strength of the research is that patients were randomly selected to take part in the study, as the aim of a randomisation method is to minimise the possibility of confounding or bias in the experimental design (Bland, 2000). Although several types of randomisation have been used in many studies, the study by Wilk et al. (1994) does not mention which specific randomisation system was used, and that may have led to bias. Additionally, the rest interval between all hop tests is not mentioned, despite the rest period being an important element during any test protocol, as it may avoid muscles being overloaded (Reid et al., 2007).

Greenberger and Paterno (1995) examined the relationship between quadriceps muscle strength and functional performance using a one-legged hop test for distance. Twenty healthy subjects completed isokinetic strength testing of the quadriceps muscle using a Kinetic Communicator at a speed of 240 degrees/sec and a one-legged hop test for distance. All tests were applied to the dominant and non-dominant legs. This study reports a very strong correlation between muscle peak torque and distance hopped for both the dominant leg and the non-dominant leg. However, the isokinetic muscle strength test was performed at a high speed of 240 degrees/sec.

Pincivero et al. (1997) recruited 37 participants (21 males, 16 females) with no previous history of injuries to their lower extremities. This study reported a relationship between a single-leg hop distance test and isokinetic variables (peak torque, peak torque to body weight, total work, and average power) for the hamstring and quadriceps muscles of both limbs for each test speed ranging between $r = 0.33$ and 0.69 at a speed of 60 degrees/sec., and $r = 0.33$ and 0.67 at speed of 180 degrees/sec. Each participant completed three trials in a single-leg hop distance test on the dominant and non-dominant legs, before completing isokinetic strength testing using the Biodex System II. The authors assessed muscle strength using Biodex System II for quadriceps and hamstring muscles at two different speeds, 60°/sec. (5 repetitions) and 180°/sec. (30 repetitions). However, it can be difficult to maintain the same level of speed with the same level of muscle performance when performing 30 repetitions at speeds of 180°/second, because the breakdown process of lactic acid within the muscles increases the absorption of lactate and hydrogen ions in the blood, and that may lead to a reduced ability of these muscles to exert force, which will finally result in muscle fatigue (Fleck and Kraemer, 2004). Consequently, the rationale for reducing the possibility of fatigue during high intensity exercise is to recommend frequent sessions followed by sufficient rest periods (Baechle and Earle, 2008).

Keays et al. (2003) assessed the relationship between knee muscle strength and functional stability pre- and post-ACL surgery. Thirty-one subjects with an ACL rupture were recruited prior to surgical reconstruction using the same procedure, which is an important strength of this study. However, there is no indication of a power calculation which, as noted above, could have affected the results. An isokinetic muscle strength test for the quadriceps and hamstrings was performed at different speeds, 60°/sec. and 120°/sec. Functional stability was tested using side steps, a shuttle run, single and triple hop tests. The results demonstrate that there was a relationship between quadriceps muscle strength and functional stability for these measures both pre- and post-surgery; whilst there was no correlation between hamstring muscle strength and functional stability for either measure, pre- or post-surgery. All the subjects underwent the same operative procedure- a semitendonosis and gracilis tendon graft-performed by the same surgeon. This process should give more accurate results, as each surgeon has his/her own technique and procedure during surgery, which could influence recovery and performance.

In summary, many studies have confirmed that single-leg hop tests are able to reflect functional limitations in the lower extremities; however, their ability to discover specific deficiencies remains unclear (Barber et al., 1990; Noyes et al., 1991).

It has been stated that drop landing activities require large eccentric forces from the hip extensors, quadriceps, and ankle plantar flexors to control lower extremity joint flexions and to decelerate the body (McNitt-Gray, 1993). However, there is a lack of literature available on exploring the relationship between hip extensor and ankle plantar flexor muscles and hop tests, which might have a role in hop performance.

1.16.3.2 Strength Assessment Reliability

The Biodex System isokinetic dynamometer is a reliable measurement tool, and several studies (Feiring et al., 1990; Lund et al., 2005; Tsiros et al., 2011; Webber and Porter, 2010; Claiborne et al., 2009) have examined the test-retest reliability of the Biodex dynamometer. Researchers have stated that it was a reliable measurement tool for knee flexion and extension, ankle plantar flexion, and hip extension isokinetic strength assessment. Feiring et al., (1990) carried out research with a healthy sample to assess the test-retest reliability of the Biodex isokinetic concentric muscle action for knee extension/flexion; they used the parameters peak torque and work. Nineteen healthy subjects aged between 20 and 35 were tested bilaterally for knee extension and flexion at different speeds 60, 180, 240, and 300°/sec., using the standard Biodex protocol. One week following the pre-test, a post-test was administered utilising identical protocol. The ICC of the extension values ranged from 0.95 to 0.97 for peak torque, and from 0.95 to 0.97 for work. While the ICC flexion values ranged from 0.82 to 0.99 for peak torque, and from 0.93 to 0.96 for work. This study concludes that the isokinetic concentric muscle action of the Biodex dynamometer is reliable for test-retest data of peak torque, and single repetition work.

In the study by Lund et al., (2005), the aim was to evaluate the reliability of the Biodex System 3 PRO dynamometer for both extension and flexion over the knee joint at speeds of 60˚/ sec. Thirteen (four men, nine women) healthy participants were evaluated five times using the Biodex System and dynamometer. Twenty minutes was the interval time between the first four tests, and seven days between tests four and five. This study has demonstrated excellent reliability with respect to knee flexion and extension, and the ICC ranged between 0.89 and 0.98. In a study by Tsiros et al., (2011), the aim was to use the Biodex Isokinetic Dynamometer with children to assess the test-retest reliability of knee flexor and extensor strength. They tested the peak isometric knee extensor and peak isokinetic knee flexor torques of both limbs two times in eleven children aged between 10 to 13 years old, seven to 10 days apart. This study revealed that peak torque was higher in the dominant leg ($p \leq 0.006$), and peak isometric knee extension torque was 8.4% higher in the second testing session. Peak isokinetic knee extension and flexion torque both had ICCs of 0.96. This study concludes that the dynamometer provides a reliable means of assessing knee strength in children aged 10 to 13 years, with excellent test-retest reliability for isokinetic knee flexion and extension.

Webber and Porter (2010) investigated the reliability of isokinetic ankle measures in older women. Ankle dorsiflexion (DF) and plantar-flexion (PF) measures were examined twice, one week apart, by the same examiner. This study concludes that adequate reliability results were shown in both tests, ICCs for the DF tests ranged from 0.76 to 0.97, and ICCs for the PF tests was between 0.58 and 0.93. In the study by Claiborne et al., (2009), the aim was to determine the test-retest reliability of isokinetic hip torque using the Biodex Isokinetic Dynamometer. Thirteen healthy adult subjects participated in two experimental tests, separated by approximately seven days. During each test, isokinetic hip torque was examined at a velocity of 60˚/sec. Subjects completed three maximal-effort concentric and eccentric muscle contractions separately, for both right and left hip flexion/extension. Motions that demonstrated high torque reliability (ICC range = 0.81- 0.91) included concentric hip flexion (right and left), extension (right), and eccentric hip flexion (right), and extension (right and left). Motions with moderate torque reliability (ICC range = 0.49 - 0.79) included concentric hip extension (left), and eccentric hip flexion (left).

The reliability of isokinetic assessments of the knee extensor and the flexor muscles using the Con-Trex isokinetic dynamometer was assessed by Maffiuletti et al. (2007) with thirty healthy participants (15 males, 15 females); they were tested and then retested a week later for maximal strength (isokinetic peak torque, work, power and angle of peak torque). All strength data, apart from angle of peak torque, for the knee extensor along with the flexor muscle groups, revealed moderate-to-high reliability, and ICC higher than 0.86, with the highest reliability recorded for concentric peak torque of the knee extensor muscles (ICC = 0.99), and insufficient to moderate ICC for the knee flexor muscles ranged between 0.78-0.81. These findings establish the reliability of isokinetic measurements using the Con-Trex machine, as explained previously in the study by Pincivero et al. (1997), which indicates the extension and flexion knee muscles reliability during concentric manoeuvre at a speed of 60˚/sec for the peak torque, peak torque to body weight, and total work ranging from 0.76 to 0.97.

1.16.4 Force Production Assessment and Different Jump Activities

A critical aspect of dynamic athletic performance is muscular power, particularly for sports requiring high force generation over a short period of time (Newton and Kraemer, 1994). Evaluating power output during the SJ activity can be seen as a common theme in the literature (Cronin et al., 2004; Dugan et al., 2004; Duthie et al., 2002; McBride et al., 2002). Moreover, jumping is a complex movement that requires complex motor coordination between the upper and lower segments of the body (Markovic et al., 2004). The propulsive action during a vertical jump from the lower limbs has been considered appropriate for examining the explosive characteristics of sedentary persons and elite athletes (Bosco and Komi, 1979; Bosco and Viitasalo, 1982). During the last 20 years, two vertical jump tests have received a lot of attention because of the effect of pre-stretching and the possibility of discriminate leg contribution: the bilateral SJ and the CMJ. These have been examined by means of contact mats or force plates (Komi and Bosco, 1978). The biomechanical features of these two vertical jumps allow the possibility of assessing the contractile characteristics of people, and the effect of pre-stretch (Bosco and Komi, 1979; Bobbert et al., 1996; IngenSchenau et al., 1997).

Isometric force and RFD are usually measured to evaluate athletic qualities, monitor adaptations to training (Haff et al., 2008), and determine the relationships between these variables and values of performance during dynamic sporting activities such as vertical jumping (West et al., 2011; Kawamori et al., 2006). In the study by West et al. (2011) the authors included thirty-nine professional rugby league players. After forty-eight hours of trial familiarisation, participants applied a maximal IMTP with approximately 120-130˚ bend at the knee, and CMJ. Force-time data were processed for PF, peak RFD, and force at 100 milliseconds (F100ms). Pearson's product moment correlation with significance set at $p < 0.05$ was used for data analysis. The PF during IMTP was not correlated to dynamic performance (CMJ height); however, when normalising the data to body weight, it was moderately correlated with CMJ height. In addition, moderate correlations were found between peak RFD during IMTP and CMJ height. The F100ms during IMTP was not related to CMJ height, however, when normalising the data on the F100ms to body weight, it was moderately correlated to CMJ height. Therefore, this study provides evidence that values of maximal strength and explosiveness from isometric force-time data are correlated to jump performance in professional rugby league players. In the study by Kawamori et al. (2006), the aim was to examine the relationship between IMTP force-time dependent variables and the force characteristics of vertical jump performances using a standard testing protocol. The data indicated that PF values of IMTP were strongly correlated with PF, peak RFD, and peak power of CMJ ($r = 0.87$, 0.85, and 0.95 respectively). However, peak RFD of IMTP had no correlation with vertical jump performances. Another study by Mcguigan et al. (2010) aimed to determine the relationships between measures of the IMTP force characteristics, which are PF and maximum RFD with VJ performance (height) in recreationally trained men. The results indicate that there were very strong correlations between VJ height and isometric med-thigh pull PF. However, there were no correlations with maximum RFD values. This study concludes that the PF during IMTP provides an efficient method for assessing VJ height in recreationally trained individuals.

1.16.4.1 Force Production Assessment Reliability

SJ and CMJ data reliability and validity are still limited regardless of the fact that they have been extensively used in the laboratory (Markovic et al., 2004). Arteaga et al. (2000) and Viitasalo (1988) have reported reliability values, and coefficient of variation, in both SJ and CMJ of 5.0-6.3% and 4.3-6.3%, respectively. Additionally, high test-retest reliabilities have been reported by Harman et al. (1990) for the great majority of biomechanical variables examined during SJ and CMJ performance (from 0.94 to 0.99). However, in the previously mentioned studies, the sample size was small (20 participants). It has been stated in the study by Hopkins (2000) that reasonable precision for estimating reliability requires approximately 50 subjects performing over at least three trials. Furthermore, excellent reliability results for SJ and CMJ have been reported by Markovic et al. (2004), ranging between 0.97 and 0.98, and their conclusion was that the most reliable and valid tests are CMJ and SJ for estimating the explosive power of the lower extremities in physically active men. SJs and CMJs have also reported very high test-retest reliability results in the adult population (Bosco and Viitasalo, 1982; Bosco et al., 1983; Viitasalo and Bosco, 1982). However, it has been shown that the reliability of these tests depends on the age or skill of the group being evaluated. Another reliability study has been conducted with children aged between six to eight years (Acero et al., 2011). This study aimed to determine the within-day and between-days reliability of SJ and CMJ in fifty-six children. The results show that the CMJ test has high reliability. The results of both tests measured using ICC (ICC $\geq$ 0.95), while the ICC for the SJ test had a high value of 0.99 only in within-day tests.

Moreover, the reliability of some variables examined during single and repetitive CMJs has been stated previously (Theodorou and Cooke, 1998; Bosco et al., 1983). These variables have also been used to evaluate the impact of athletic performance (Kraemer et al., 1996; Hoffman et al., 2002; Hoffman et al., 2003; Howell et al., 2001). Power examined during 60 seconds of a repeated CMJ has previously been stated to have reliable ICC of 0.95 (Bosco et al., 1983). In another study involving a high number of repetitions, Alemany et al. (2005) investigated the reliability of peak power, mean power, peak velocity, mean velocity, and work during 30 seconds of continuous squat jumps using 30% of one repetition maximum. The results show that ICCs ranged between 0.80 and 0.96. Cormack et al. (2008) investigated the reliability of different measures collected during single and repeated CMJs' performance in an athletic population. This study has revealed that a number of CMJ1 and CMJ5 variables show good reliability overall. For the CMJ1, mean force was the most reliable variable with coefficient of variation (CV) of 1.08%. In the CMJ5, flight time and mean force displayed the highest reliability, with CV of 1.88% and 1.57% respectively. Another study by Myer et al. (2012) was carried out with thirty-three unilateral ACLR athletes, 10 males and 23 females, who were assessed by a physician to be able to return to their sports after ACL surgery and rehabilitation. They performed the single-legged vertical hop test continuously for 10 seconds on a force plate. Maximum VGRF was recorded during each single limb landing; however, during such tasks this is likely to represent the impact force rather than the active braking (eccentric) phase unless the force measure is aligned with the lowest displacement of the centre of mass for each subject. The authors also assessed the propulsion phase using hop height derived from flight time, however this can easily be influenced by hopping / jumping technique especially if a ‘tuck jump’ is performed. The single limb symmetry index was measured as the ratio of the tested divided by the uninvolved leg, expressed as a percentage. This study concludes that deficits in unilateral force development during vertical hop height, and absorption in normalised VGRF, persist in an athlete's single-leg performance after ACL surgery and full return to sports. These symmetry deficits seem to be independent of time after ACL reconstruction.

Moir et al. (2005) investigated the bilateral SJ reliability in nine physically active men using a force platform. The measurements of PF, peak RFD, takeoff velocity, and peak power were reported for each jump. Reliability was evaluated by calculating ICC and coefficient of variation associated with the force variables, which found moderate to excellent reliability in SJ force characteristics. The ICC results for PF was (0.96), peak RFD (0.53), takeoff velocity (0.93), and peak power (0.97). These results suggest a high level of test-retest reliability when it comes to force measures when testing physically active men. Sheppard et al. (2008) investigated the bilateral CMJ reliability in a total of 26 subjects. The measurements of PF, peak RFD, peak velocity, peak power, and relative power (normalised to body weight) were reported for each jump. Reliability was evaluated by calculating ICCs. This study found that the ICC for PF was excellent (0.96), peak RFD was moderate (0.43), peak velocity was low (0.25), peak power was excellent (0.80), and relative power was (0.74), which suggests that the force characteristics of CMJ are reliable when using this test methodology. Another study by Mizuguchi et al. (2015) investigated the test-retest reliability of the force characteristics of the CMJ in twelve participants who performed the CMJ in two separate sessions (48 hours apart). They indicated an excellent ICC of 0.78 for RFD for the CMJ, which suggests that RFD can be used as a reliable variable to measure the performance of CMJ.

For the isometric contraction test, a study by Angelozzi et al. (2012) examined the RFD to 30% (RFD_{30}), 50% (RFD_{50}), and 90% (RFD_{90}) of maximal voluntary isometric contraction (MVIC), as an additional outcome measure to determine readiness to return to sport after ACL reconstruction. Forty-five professional male football players who underwent an ACL surgery were recruited. The KT1000 instrumented arthrometer was used at pre-reconstruction, and six months and at 12 months after ACL surgery. MVIC, RFD_{30}, RFD_{50}, and RFD_{90} testing was done pre-injury, as part of standard preseason evaluation, and at six months and 12 months post-ACL reconstruction. The results of this study suggest that RFD criteria may be a useful adjunct outcome measure for the decision to return to sports following ACL reconstruction. Furthermore, the reliability of isometric med-thigh clean pulls has been investigated by Kawamori et al. (2006). The results of this study show excellent values for both variables, which are PF and peak RFD, with ICC of 0.97 and 0.96 respectively, and both the isometric PF and dynamic Peak RFD were strongly correlated with vertical jump performances.

Another test-retest reliability study was carried out by Comfort et al. (2015) to determine the effect of knee and trunk angle on kinetic variables during the IMTP. The study’s aim was to investigate whether different knee-joint angles of 120°, 130°, 140°, and 150° and hip-joint angles of 125° and 145°, including the participants’ preferred posture, might affect force, maximum RFD (mRFD), and impulse during the IMTP. Intraclass correlation coefficients demonstrated high within-session reliability for all kinetic variables determined in all postures, apart from impulse measures during the 130° knee-flexion and 125° hip-flexion posture, which resulted a low to moderate reliability, while between-sessions testing showed high reliability for all kinetic variables. There were no differences found in PF; in mRFD; in impulse at 100 ms; in 200 ms, or in 300 ms across postures. It is therefore suggested that when evaluating athletic development, strength and conditioning coaches and researchers should use the posture that the individual participants prefer, as this is comparable across a range of hip- and knee-joint angles.

Another reliability study was carried out by Haff and his colleagues (2015). The aim of this study was to compare the various methods reported in the scientific literature used to assess the RFD during isometric mid-thigh clean pull, to discover which have the highest reliability. The participants in the study were twelve female division I collegiate volleyball players, and the reliability of a number of methods used measure the RFD during the isometric mid-thigh clean pull was tested. The participants were made familiar with the isometric mid-thigh clean pull, and they were asked to attend regular strength training. Two isometric mid-thigh clean pulls were used, and two minutes rest was provided between each go. All trials took place in a custom isometric testing machine which included a step-wise adjustable bar attached with a force plate, for measuring ground reaction forces. Throughout planned time zone bands (0–30, 0–50, 0–90, 0–100, 0–150, 0–200, and 0–250 milliseconds), the RFD was calculated by dividing the force at the end of each band by the band's time interval. With the use of 2, 5, 10, 20, 30, and 50 milliseconds sampling windows, the peak RFD was then calculated. The average RFD was calculated by dividing the PF by the time to achieve PF. All data were analysed using intraclass correlation alpha (ICCa) and 90% confidence intervals and the coefficient of variation (CV). All predetermined RFD time bands were reported reliable based on an ICCa > 0.95 and a CV < 4%. However, the average RFD failed to meet the reliability criteria set for this study. Overall, predetermined RFD time bands should be used to quantify the RFD, and the method used to evaluate the RFD during an isometric mid-thigh clean pull influences the reliability of the measure.

1.16.5 Two-Dimensional Assessment and Different Jump Activities

Many screening tests have been used in the literature to evaluate dynamic knee valgus (Munro et al., 2012). These tests have involved the SLS (Willson and Davis, 2008; Willson et al., 2006; Zeller et al., 2003), drop vertical jump (Hewett et al., 2005; Noyes et al., 2005; Herrington and Munro, 2010), single-leg landing (Lawrence et al., 2008), and drop landing (Decker et al., 2003). 3-D motion analysis has been used in most of these studies to analyse lower limb biomechanics. In clinical research, either 3-D or 2-D motion-analysis systems are available for measuring functional movement. 3-D has been considered the gold-standard measurement tool for gait analysis (Munro et al., 2012; Whittle, 2007; Kirtley, 2006). However, 3-D systems are very expensive and need experienced operators, which means that the 2-D systems may be more useful in practice (Munro et al., 2012; Rowe, 1999). 2-D analysis has been used to evaluate knee-valgus angle in healthy, athletic, and injured populations (Willson et al., 2006; Noyes et al., 2005).

FPPA is the angle that has been commonly measured in the literature to evaluate dynamic knee valgus using 2-D video analysis. The FPPA is known as the relative position/angle of the femur to the tibia. Different authors have used either the line of the thigh or a marker on the ASIS to determine this, however, ASIS would be more preferable to use than thigh line because it is known as identifiable landmark. To date, only two within-day reliability studies of FPPA using 2-D analysis with ICC have been presented (Munro et al., 2012; Willson et al., 2006). Therefore, future work on the reliability of 2-D FPPA is required. Munro et al. (2012) aimed to examine the reliability and measurement errors of the 2-D analysis of lower limb dynamic valgus in 20 recreationally active university students. Subjects applied single-leg squat, drop jump, and single-leg landing tests. The results show that women in all tests had significantly higher FPPA, except for the left single-leg squat test. Within-day ICC results stated good reliability and ranged between 0.59 and 0.88, and between-days ICCs demonstrated good to excellent results, ranging from 0.72 to 0.91; while standard error of measurement and smallest detectable difference data ranged from 2.72° to 3.01° , and from 7.54° to 8.93° , respectively. Willson et al. (2006) aimed to compare the FPPA of the knee during a 45° SLS of the lower extremity among male and female athletes. This study revealed that males and females shifted in opposite directions during the SLS test (F (1,42) = 5.05, *p* = 0.03). Males typically moved toward more neutral alignment (*p* = 0.066), while females tended to move toward more extreme FPPA throughout SLS (*p* = 0.056).

1.17 Gaps within the Current Literature and Strategies for Filling the Gap

Although several studies have examined the relationship between lower extremity balance, TTS, muscle strength, force generation, and 2-D knee kinematics after hopping as single tasks, no study has ever examined the interrelationship between all of these factors and hop performance in both healthy and six to nine months post ACL reconstructed participant groups. In addition, no study has provided reference values for each of the individual tests for both groups, or defined the typical hop distance mean for both groups. Moreover, as a result of the different methods and parameters used in the aforementioned studies, such as variability in testing duration, testing tools, and populations, this situation may require further investigation. Therefore, given this gap in the literature, there is adequate justification for conducting this study to investigate the relationship between all of these factors and hop performance in both healthy and six to nine months ACL reconstructed participant groups.

1.18 Contextualising the Assessment Methods

In order to assess those factors which are significant in the performance of hop tests, it first needs to be established whether the individual tests undertaken are reliable, if there is symmetry of performance between limbs, and what the reference values are when undertaking these tests. The first part of this thesis will focus on these questions.

This will be followed by investigations into the association between individual tests and hop test performance in asymptomatic individuals and those with an ACL reconstruction.

1.19 Aims of the Project

The overall aim of the work contained within this thesis is to have a better understanding of hop test performance and the factors which influence it. In order to answer this question, the work undertaken has been broken down into a number of elements with specific aims:

1. Investigate the reliability of the individual tests which consist of hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic strength testing to establish the measurement error of these.
2. Investigate the reference values for each of the individual test procedures, as well as if limb symmetry exists for hop tests and isokinetic muscle strength tests. Attempt to establish reference performance ranges for the tests so sub-optimal performance can be identified in either group in a future study or what normal limb symmetry indexes for both tests (hop tests and isokinetic muscle strength tests) are.
3. Investigate the relationship between all of the tests and hopping performance in a healthy population.
4. Investigate the relationship between all of the tests and hopping performance in participants six to nine months post ACL reconstruction.

Chapter (2)

Methodology and Instrumentation

2 Chapter 2: Methodology and Instrumentation

2.1 Procedure

For each participant, the measurements of their performance during all five tests were taken for both legs individually. The participants removed any clothes covering their lower limbs such as socks, and have also been asked to wear loose shorts or underwear. The participants' shirts were held up using adhesive tape, and male participants were asked to remove their shirts if they preferred. Before starting the test, the participants performed a warm up on a cycle ergometer (Monark, Ergomedic 874 E) for five minutes with minimal resistance (75W) (Woods et al., 2007). Before starting any of the following tests, the participants were asked to perform practice trials (maximum of three and minimum of one) for each of the tests to ensure familiarity with the procedures (Phillips and van Deursen, 2008). After finishing the practice trial/trials, each test was performed in a random order (Phillips and van Deursen, 2008). Three successful trials were finally collected from each test, while the unsuccessful trials are explained for each test in depth in the following paragraphs. A two minute rest period was given in between each test (Corriveau et al., 2000), with half a minute rest between trials.

2.1.1 Single-Leg Hop Tests

Hop test performance was assessed using a normal metric tape measure. There were two types of hop tests which were used in this study- horizontal single-leg hop for distance, and crossover hop tests. The procedure for the hop tests was as explained in the study by Ross et al. (2002): an 8m strip of tape was placed on the floor, and the start line was labelled using a 0.3m strip of tape placed perpendicular to the 8m strip of tape secured to the floor. The participants then performed three practice trials for each of the hop tests in the following order: single-leg hop for distance and crossover hop for distance. After finishing the practice trials, three test trials were performed for each test. Successful attempts were defined as being when the participant hopped and landed with complete stabilisation on one leg for three seconds. There were no restrictions given to participants regarding the use of arm movements during the hop tests (Munro and Herrington, 2011). The participants achieved three maximum hop attempts with complete stabilisation after landing for three seconds. Unsuccessful attempts were when the participant hopped and touched the ground with their non-weight bearing leg during landing, or failed to hop within the limited marked distance; all failed hop attempts were counted and noted but were not processed (Phillips and van Deursen, 2008).

Each participant’s leg lengths were measured during the first test using a standard tape measure, and the measurement was from the anterior superior iliac spine (ASIS) to the distal tip of the medial malleolus while participants lay supine. Leg length was used during data analysis to normalise excursion distances (Munro and Herrington, 2011).

2.1.1.1 Single-Leg Hop for Distance

The participants started by standing on one leg, with their toe on the marked starting line. They were then instructed to hop as far as they could horizontally and land on the same leg. The distance hopped from the starting point to the place where the participant's heel touched the floor was taken (see Figure 2.1). Hop data was normalised to limb length by dividing the distance covered by leg length and then multiplying by 100, which resulted in a percentage value (Munro and Herrington, 2011). Once they had finished the test, the participants performed the same procedure using the other leg.

2.1.1.2 Crossover Hop for Distance

As explained above, the participants started by standing on one leg, with their toe on the same starting point. When they hopped using the right leg, they stood on the right side of the 8m strip of tape. However, when they hopped using the left leg, they stood on the left side of the 8m strip of tape. The participants were instructed to take three repeated maximal horizontal hops on the same leg, and each time hop crossed over the strip of 15-cm-wide tape. The distance hopped from the starting point to the place where the participant's heel landed on the final (third) hop was taken (see Figure 2.1). Once they had finished the test, the participant applied the same procedure with the other leg.

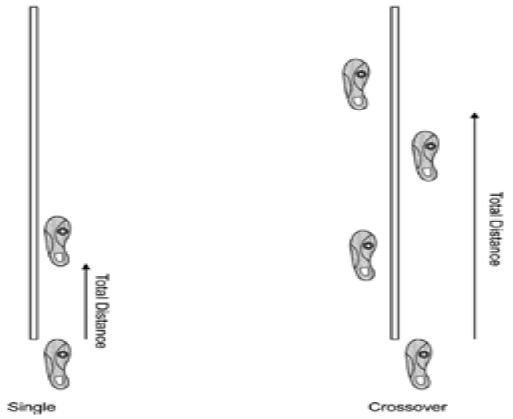


Figure 2.1. Two single-leg hop tests procedure (Munro and Herrington, 2011)

2.1.2 Frontal Plane Projection Angle

The FPPA was assessed using a single camera, Casio Exilim, EX-F1 (Casio Computer CO Limited, Japan), at a standard sampling frequency of 30 fps, positioned on a tripod at a height of 80cm from the floor to the middle of the lens, and 2.5m away from an X-shaped marker which was placed as a reference for the central point on the floor (see Figure 2.2). The zoom lens of the video camera was set at a standard 1x optical zoom throughout all trials in order to standardise the camera position between participants. The reason behind placing the camera on a tripod at a height of 80cm and 2.5m away was to ensure that the video included the lower limbs, trunk and shoulders of the participants with different heights. Each participant was filmed, before starting any of the individual tests, using a calibration frame (1m ×1m) for five seconds. The calibration distance was set 2.5m away from a camera (frontal plane) just above the X mark which was placed on the floor. This calibration was used for data analysis; the process of data analysis is explained in depth in the data analyses section.

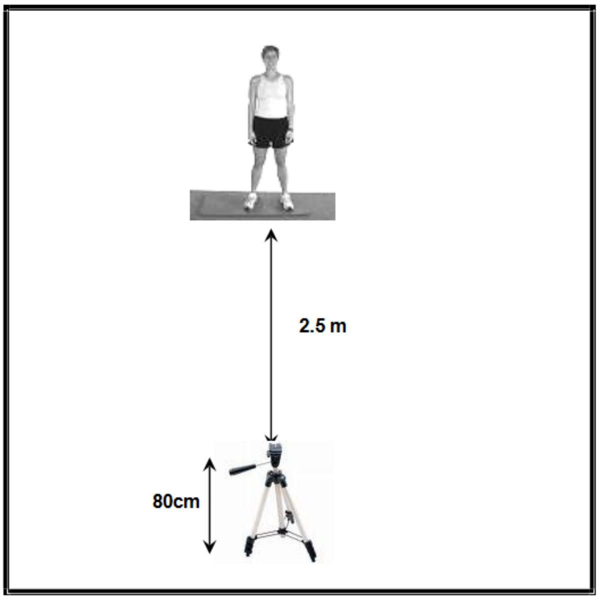


Figure 2.2. Camera's position

In order to examine the FPPA, three black markers were placed directly on the participants' skin before starting the test using a black marker on the following points:

1. Anterior superior iliac spine (ASIS).
2. Midpoint of the knee joint (midpoint of the medial and lateral femoral epicondyles).
3. The middle of the ankle mortise anatomical landmark.

All markers were placed by the same experimenter, and the midpoints were determined using a standard tape measure. These markers were placed in order for FPPA of the knee to be determined (see Figure 2.3).

Figure 2.3. Anatomical marker placement

2.1.2.1 Single-Leg Squat

Participants were instructed to stand on one leg, keep the other limb off the floor, with hands crossed behind their trunk in order to allow all markers to be visible. They were asked to squat down to 45° (estimated visually) and then return to a normal position without losing their balance. During practice trials, knee flexion angle was checked using a standard goniometer (Gaiam-Pro) then observed by the examiner throughout all trials. There was also an electronic counter used for each trial over five second period in which the first count starts the movement, the third shows the lowest point of the squat and the fifth shows the end. In order to control the degree of lower limb rotation during squatting, the participants were instructed to place their foot on the X-shaped marker, which was placed on the floor, with their foot pointing straight ahead. Acceptable trials were when participants maintained balance and squatted to the desired depth of approximately 45° of the knee joint. Once the test was finished, the participant applied the same procedure using the other leg.

2.1.2.2 Single-Leg Hop Landing

The FPPA in this test was assessed during the single-leg horizontal hop for distance. As explained earlier in the single-leg hop for distance test, participants were asked to hop forward on one leg as far as possible, and land with complete stabilisation within the area of the X-shaped marker which was placed on the floor 2.5m far away from a camera (the hop was applied after adjusting the starting point). The participants hopped to the X-shaped marker (or nearby) from a starting point based on their individual hop distance achieved during the practice trials, to ensure that the landing was at a point ± 30 cm from the X-shaped marker, to accommodate the calibration. After landing, the participants were free to move their arms as required and to help with balance following landing. Unsuccessful attempts were when the participant hopped and touched the ground with their non-weight bearing leg during landing (Phillips and van Deursen, 2008), or failed to hop within the limited marked distance. The participant needed to land with their foot in line with the camera to ensure that the appropriate calculation of the FPPA could be achieved. If the individual landed with their foot too abducted or adducted this trial was repeated as this will affect the measurement of the FPPA. Once they had finished the test, the participants followed the same procedure with the other leg.

2.1.3 Balance Tests

These tests were performed using a portable Kistler Force Plate, 600 mm x 400 mm, Type 9286AA (Kistler, Winterthur, Switzerland) which was interfaced with a laptop computer with force time data collected using Bioware software v 5.1.1.0. While setting up the tool and before starting the test, two wooden platform attachments were connected to the Kistler force plate to make it convenient and safe, all on one level, for the participants to perform the test. There were three different balance tests- two static tests to measure the sway area and one dynamic test to measure TTS. Bioware software was downloaded to a laptop which was connected to the force plate; this software was set by the researcher for the two different methods. For the static (sway area) test, the duration force-time data was collected for 10 seconds at a frequency of 50 Hz. For the dynamic (TTS) test, the duration force-time data was collected for six seconds at a frequency of 1000 Hz. The detailed procedures of the three tests are explained below.

2.1.3.1 Straight Leg Static Balance Test (Sway Area)

Static balance was measured during standing in a straight leg position on the force plate on one leg and remaining as motionless as possible for 10 seconds until the participant was instructed to relax (Ross et al., 2009). Participants kept their eyes open, hands on hips and the non-weight bearing leg was slightly flexed at the hip and knee. The foot position was in a neutral position pointed straight forwards (see Figure 2.4). Once they had finished the test, the participant applied the same procedure with the other leg.

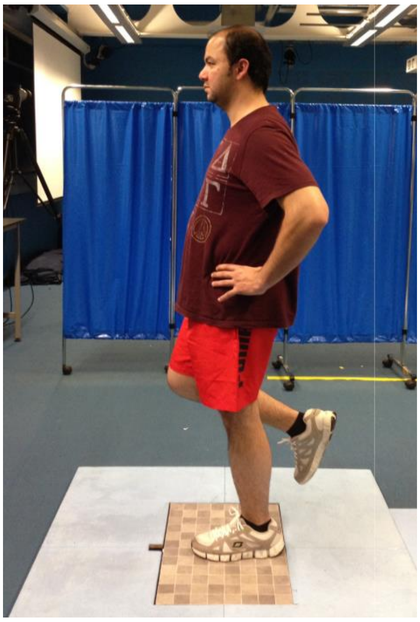


Figure 2.4. Straight leg static balance test

2.1.3.2 Flexed Leg Static Balance Test (Sway Area)

For this test, the procedure was the same as in the study by Ross et al. (2009), as explained above, but the knee angle for the tested leg was in a flexed position at approximately 30° using a goniometer. The rationale for using 30° of knee flexion was because it has been reported that strain in the ACL during simultaneous hamstring and quadriceps activity is significantly high from full extension to 30° of flexion (Renstrom et al., 1986). Static balance was measured during standing in a flexed leg position on the force plate on one leg and the participant remained as motionless as possible for 10 seconds until they were instructed to relax. Participants kept their eyes open and hands on hips, and the non-weight bearing leg was slightly flexed at the hip and knee. The foot position was in a neutral position pointed straight forward (see Figure 2.5). Once they had finished the test the participant applied the same procedure with the other leg.

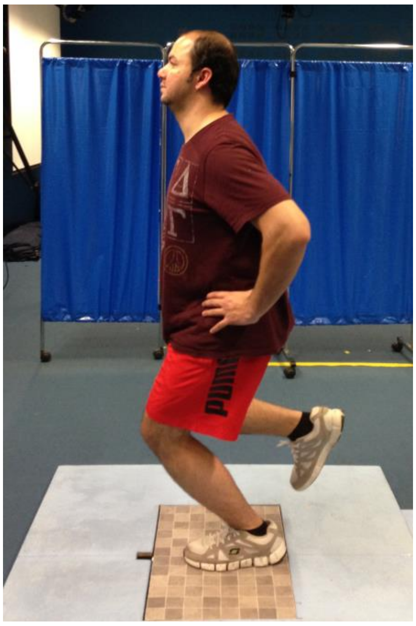
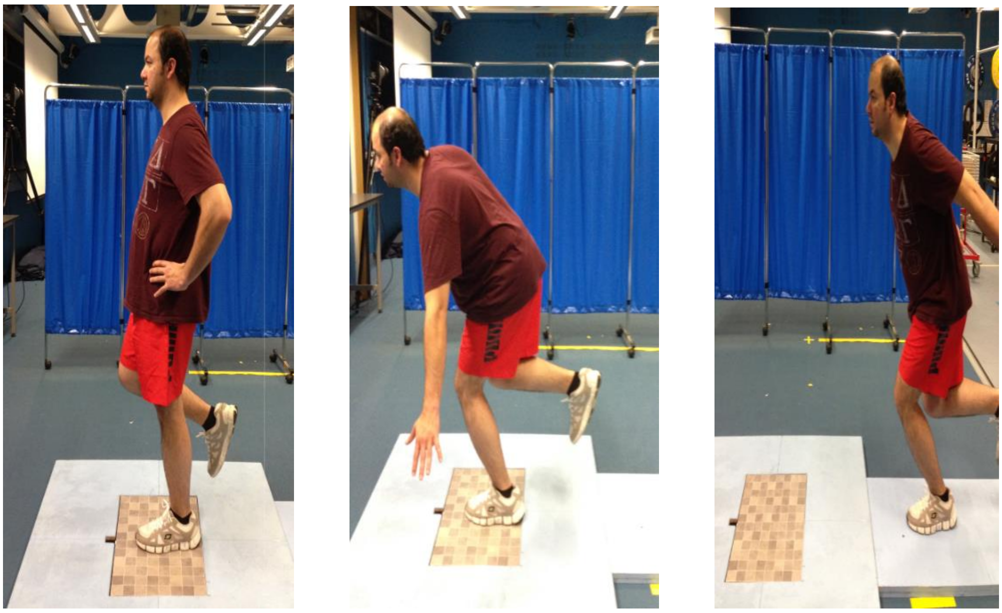


Figure 2.5. Flexed leg static balance test

2.1.3.3 Dynamic Balance Test (TTS)

From the previously mentioned single-leg horizontal hop for distance test, the maximum (furthest) distance of the three trials was reported (Phillips and van Deursen, 2008). Then 80% of the maximum hop distance value was calculated and recorded to be used as a distance hop from the starting point of the test to the middle point of the force plate. The rationale for using 80% as a test distance was to ensure that each participant was able to land and maintain their balance with their foot completely on the force plate; 80% of maximum distance was difficult and challenging but still achievable. Coloured tape was used to mark the starting point for the hop-land trials after calculations. Finally, the participants hopped from the starting point and landed on the force plate with one leg and remained as motionless as possible for six seconds until instructed to relax. After landing, they kept their eyes open and the non-weight-bearing leg slightly flexed at the hip and knee. The participants were free to move their arms as required to help in balancing following landing; once completely stabilised hands were placed on hips (see Figure 2.6). Unsuccessful attempts were when the participants hopped and touched the ground with their non-weight bearing leg during landing or failed to hop with a proper distance (Phillips and van Deursen, 2008). Once they had finished the test, the participant applied the same procedure with the other leg.



C B A

Figure 2.6. Dynamic balance test (TTS):

A: Hopping forward from the taped line to the force plate on one leg, **B:** Landing on the same leg on the force plate and trying to maintain balance and keep it under control, **C:** Finishing position with hands on hips.

2.1.4 Dynamic and Static Force Generation Tests

All tests were performed using an FT 700 Power Cage, integrated with a 400 series Force Plate 795 mm x 795 mm (Fitness Technology Inc, Adelaide, Australia). The sampling frequency of the force plate was 600 Hz. Before using this tool, calibration was applied following the manufacturing guidelines; briefly, two known masses were placed over the force plate to determine the calibration coefficient. The force plate was zeroed prior to each trial.

There were four different tests which included three dynamic tests and one static test. These tests are explained in detail in the following sections.

2.1.4.1 Single-Leg Squat Hop Test

The participants were asked to stand on one leg and then were instructed to semi-squat to about 45° (visually estimated) for three seconds prior to hopping vertically as high as possible from a semi-squat position, without a countermovement. The test period was set for 5 seconds. To make sure that the participants did not perform any countermovement in the lower extremities before they hopped, raw force-time data was checked after every trial to make sure that there were no changes in the force-time data (remain stable without a dip in the force). If there was a countermovement, as evident from a visual inspection of the force-time data, the trial was repeated and not collected.

The participant's hands were kept on their hips during the test (see Figure 2.7), and the reason behind this was to avoid any excessive force that might be produced from swinging the arms (Harman et al. 1990), thereby making sure that the resultant force-time data was created by the lower limbs' performance only. Moreover, keeping the hands on the hips reduces the effect of arm motion to better reflect lower limb performance (Impellizzeri et al., 2007). Participants were required to land in the same place as take-off, and after initial contact, flexion was permitted to permit the absorption of landing forces. Once the test was finished, participants applied the same procedure with the other leg.

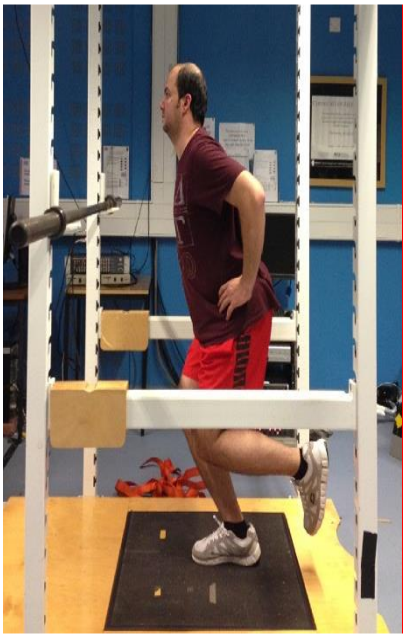


Figure 2.7. Squat hop force generation test

2.1.4.2 Single-Leg Countermovement Hop Test

Participants were asked to stand on one leg, and after an initial stationary phase of at least two seconds in the upright position as motionless as possible, the participants performed a countermovement hop as high as possible, dipping to a self-selected depth with hands kept on hips and then accelerated upward with maximal effort. The reason behind keeping both hands on hips during the test was, as explained above, to avoid any excessive force that might be produced from swinging the arms (Harman et al. 1990). Furthermore, keeping the hands on the hips reduces the effect of arm motion to better reflect lower limb performance (Impellizzeri et al., 2007). Participants were required to land in the same place as take-off, and after initial contact, flexion was permitted to permit the absorption of landing forces. The test period was set for 5 seconds. Once the test was finished, participants applied the same procedure with the other leg.

2.1.4.3 Single-Leg Ten Consecutive Hops Test

Participants were asked to stand on one leg and then were instructed to hop continuously ten times vertically as high as possible, and participants were asked to make a countermovement with the lower extremities before hopping. The test period was set for 10 seconds. The instructions were given to the participants as follows: ‘execute ten consecutive maximal vertical hops with minimal ground contact time’ and asked not to perform a ‘tucking’ movement with the leg while in flight. Participant’s hands were kept on the hips during the test. The reason behind keeping both hands on the hips during the test was, as explained above, to avoid any excessive force that might be produced from swinging the arms (Harman et al., 1990). Additionally, keeping the hands on the hips reduces the effect of arm motion to better reflect lower limb performance (Impellizzeri et al., 2007). Participants were required to perform all hops in a consecutive effort as high as possible without a pause between hops (Cormack et al., 2008). Once the test was finished, the participants applied the same procedure with the other leg.

2.1.4.4 Single-Leg Isometric Mid-Thigh Pull Test

This was the only static force test. The participants were asked to stand on one leg using their preferred position to place the bar at the midpoint of the thigh. They were asked to select the hip- and knee-joint angles that they would normally utilise to perform a mid-thigh pull, and then the bar was fixed in this position/height using lifting straps. Their preferred positions/angles were used because it was found by Comfort et al. (2015) that there is no effect on kinetic variables when the bar position on the thigh is constant, using different knee- and hip-joint angles and the preferred position during the IMTP. It was therefore suggested that when evaluating athletic development, researchers should use the posture that the individual athlete prefers; this might also help to minimise the learning effect. The participant’s hands were strapped to the bar with standard lifting straps and athletic tape. The bar was pointed to mid-thigh distance when bending both legs (participants achieved ankle dorsiflexion, knee and hip flexion, while maintaining an upright torso, with a neutral spine posture), and then they were instructed to pull the bar as fast and as hard as possible, and also to push from the lower extremities at the same time for a duration of five seconds (using a stop watch) until instructed to relax (see Figure 2.8). The test period was set for 10 seconds, whereas five seconds were given for pulling and the remaining five seconds for the instructions before and after performing the pull. Once the test was finished, the participants applied the same procedure with the other leg.

Figure 2.8. IMTP force generation test

2.1.5 Isokinetic Muscle Testing

This test was performed to measure muscle strength for both concentric and eccentric actions for knee extensor and flexor, hip extensor, and ankle plantar flexor muscles using Biodex System 4 with associated Software (Biodex Medical Systems, Inc, Shirley, New York, USA). Before starting the tests, the calibration of the Biodex dynamometer was applied according to the specifications outlined by the manufacturer's service manual. The testing speed for all muscles was concentrically and eccentrically at 60°/sec as this speed has been used a lot in the literature with hop performance (Claiborne et al., 2009; Lund et al., 2005; Keays et al., 2003; Pincivero et al., 1997; Barber et al., 1990; Feiring et al., 1990). In addition, testing at speeds below 60°/sec have been reported as not recommended speeds because of excessive shear forces and compression to the knee joint and its lack of functional significance (Wyatt and Edwards, 1981), also with a slow testing speed (below 60°/sec) the participants might get fatigued as a result of resisting longer time against the dynamometer than 60°/sec. On the other hand, with testing at speed more than 60°/sec the chances of missing some resistance and forces might be occurred as a result of the high speed of the dynamometer, therefore, testing at speed of 60°/sec should be appropriate as there is more chance of resisting against the arm and producing more forces. Also, the testing order for the joints and muscle groups (flexors, extensors) was randomised (Fousekis et al., 2010). Five maximal effort repetitions were performed and reported for every trial for each limb in a total of three successful experimental conditions (trials) (Fousekis et al., 2010). Three successful trials were recorded for each of the individual tests. To become familiar with the test procedure, participants were first asked to perform three submaximal repetitions at the same speed as during the actual protocol. A full explanation of the test procedures is explained in the following sections.

2.1.5.1 Quadriceps and Hamstring Muscle Testing

According to Fousekis et al. (2010) concerning protocol, participants were in a seated position with 90° hip angle, with the body stabilised by straps around their tested thigh, waist, and trunk, with their arms firmly across the chest to allow testing the concentric and eccentric muscle actions of both knee extensor and flexor muscles (quadriceps and hamstring). When evaluating knee flexion and extension, the axis of rotation movement of the dynamometer was aligned with the lateral femoral epicondyle. The average range of motion (ROM) when testing knee muscles was set at 0° (in full extension) to 90° (see Figure 2.9). The test was then performed with the same repetitions as explained above (5 repetitions). Once they had finished the test, the participant applied the same procedure with the other leg.

Regarding the machine ROM setup when measuring knee extensors (quadriceps), the starting position was set from full knee extension 0° to the end position of 90° of knee flexion using a goniometer, so the trials started with the eccentric muscle contraction at 0° (full knee extension) until the arm reached 90° of knee flexion, and then the concentric muscle contraction phase started to bring the arm back to the starting position (0° of full knee extension); this was performed as five repeated cycles in one trial. For the machine ROM setup when measuring knee flexors (hamstring), the starting position was set from 90° of knee flexion to the end position of 0° of full knee extension using a goniometer, so the trials started with an eccentric muscle contraction from 90° of knee flexion until the arm reached 0° of the knee’s full extension position; then the concentric muscle contraction phase started to bring the arm back to the starting position (90° of the knee flexion), and this was performed as five repeated cycles in one trial.

Knee Extensors Test Position Knee Flexors Test Position

Figure 2.9. Illustrates both knee flexors and extensors test positions

2.1.5.2 Ankle Plantar Flexor Muscles Testing

According to the protocol of Requiao et al. (2005), participants were seated on the dynamometric chair with hip flexion at an angle of 80° and the knee flexed about 30° (to isolate the knee muscles from adding any extra strength); these angles were determined using a goniometer. The tested leg was placed and strapped by an arm joint to allow knee flexion, and the body was stabilised by using straps around the waist and trunk with their arms firmly across the chest to allow testing of the concentric and eccentric muscle actions of the ankle plantar flexor muscles. Participants' feet were tightly fixed with the training shoes provided to attach them to the dynamometer, and the axis of rotation movement of the dynamometer was aligned with the fibular lateral condyle (see Figure 2.10). The average ROM when testing the ankle plantar flexor muscles, was set from 0° to 50°. All tests were performed from the maximal plantar flexion angle to the ankle neutral position angle using the same repetitions, as explained above (5 repetitions). Once they had finished the test, the participant applied the same procedure with the other leg.

Regarding the machine ROM setup when measuring ankle plantar flexor muscles, the starting position was set from full ankle plantar flexor position, which was located from 50° to the end position of 0° of the ankle neutral position using a goniometer, so the trials started with an eccentric muscle contraction from 50° of ankle plantar flexor position until the arm reached 0° of ankle neutral position; then the concentric muscle contraction phase started to bring the arm back to the start position (50°) of ankle plantar flexor, and this was performed as five repeated cycles in one trial.

Figure 2.10. Illustrates ankle plantar flexors test position

2.1.5.3 Hip Extensor Muscles Testing

According to the protocols described by Requiao et al. (2005) and Meyer et al. (2013), participants were placed in a supine position by reclining the backrest of the testing chair to allow a fully flat position; the body was stabilised using straps around their pelvis and trunk. The axis of rotation movement of the dynamometer was aligned with the flexion/extension hip joint axis (greater trochanter), and the resistance pad was placed at the distal part of the femur (see Figure 2.11). The average ROM when testing the hip extensor muscles was from 0° of hip flexion to maximal hip flexion (110°-120°). The test was then performed using the same repetitions as explained above (5 repetitions). Once they had finished the test, the participant applied the same procedure with the other leg.

Regarding the machine ROM setup when measuring hip extensor muscles, the starting position was set from 0° of hip flexion to the end position of the range, which was between 110°-120° of hip's full flexion using a goniometer, so the trials started with an eccentric muscle contraction from 0° of hip flexion position until the arm reached the range between 110°-120° of the hip's full flexion; then the concentric muscle contraction phase started to bring the arm back to the start position (0° of hip flexion), and this was performed as five repeated cycles in one trial.

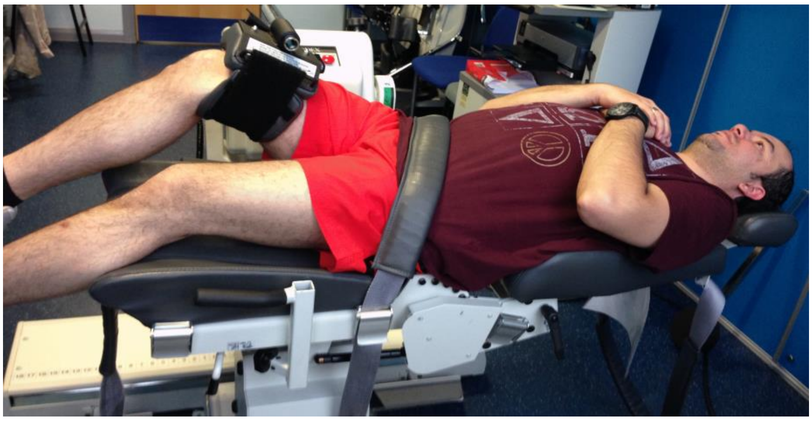


Figure 2.11. Illustrates hip extensor muscles test position

2.2 Data Processing and Analysis

2.2.1 Hop Data Analysis

As explained earlier the maximum (furthest) point reached by participants when hopping was recorded for both hop procedures, which are single-leg hop for distance and crossover hop, using a tape measure. However, each participant's leg lengths were measured also using a standard tape measure, and the measurement was from the ASIS to the distal tip of the medial malleolus while participants lay supine. Leg length was used to normalise excursion distances by dividing the distance covered by leg length and then multiplying by 100 to obtain a percentage value (Munro and Herrington, 2011). After recording the results from the three successful trials for each participant, the mean value over the three trials was calculated and reported.

2.2.2 FPPA Data Analysis

The analysis of the FPPA was undertaken in Quintic Biomechanics Software (v21, Quintic, Sutton Coldfield, UK) where FPPA was taken at the maximum knee flexion angle after landing from hop and squat (defined as the lowest point the pelvis reached). After recording the results from the three successful trials for each participant, the mean value over the three trials was calculated and reported.

The analysis process for the 2-D FPPA was done by uploading the video to the software which was taken for calibration, including the calibration frame (1m × 1m) for each participant, then designation was pressed to set the horizontal line with a total distance of 1m and before setting the vertical line with a total distance of 1m. Next, video analysis speed was set at 30 ms (in order to play the video in slow motion). Once the speed was set up, the software was then ready to analyse the collected video trials which were performed by the same participant. The video calibration process during data analysis for each participant was applied before starting the video analysis for the trials for the same participant. After this, the videos of both squat and horizontal single-leg hop land tasks were analysed. The video was played until maximum knee flexion position during both tasks. After holding the video in the maximum knee flexion position, the analysis started by joining the lines between the markers, starting from the ASIS to the midpoint of the knee joint (midpoint of the medial and lateral femoral epicondyles), and then ending by the middle of the ankle mortise anatomical landmark, as shown in Figure 2.12. The convention used for measurement was that 180 degree equals straight, angles < 180 were considered valgus, and > 180 considered varus. The resulting number was then recorded, and after that a calculator was used to calculate the final results using the following mathematical equation {180 – (the resulting number) = final result}.

Figure 2.12. Illustrates the analyses of the FPPA during SLS task

2.2.3 Balance Data Analysis

All balance data was processed and analysed using Bioware software v 5.1.1.0 (Kistler, Winterthur, Switzerland) to convert the resulting balance figures to text files. After converting the figures to text files, a spreadsheet called SWAY analysis version 04-07-09 created by Dr. Phil Graham-Smith, was used to open the converted text files and the converted numbers were placed in specific rows and columns on the spreadsheet to calculate the static (sway area) and dynamic (TTS) tasks. Microsoft excel was used to calculate and determine the following variables:

A. Static balance test as centre of pressure (COP) excursion in centimetres.

B. TTS after landing from horizontal hop test trials in seconds.

In Microsoft Excel, the average position and standard deviation of COP in the single leg balance test was calculated along X (AX) and Y (AY) axes. From this, Target sway represents an elliptical area of COP deviation measured as: 61% of a rectangle, known by two times standard deviation along the X axis multiplied by two times standard deviation along the Y axis.

For TTS, the time period from when the vertical force increases past 20 N (= INDEX (T1: T2, 20N), where T1 and T2 were the first and last time data points) to the point of lowest force post impact (=MIN(INDEX (Fz1: Fz2, peak Fz), where Fz1 and Fz2 were the first and last vertical force data points) was determined using Microsoft Excel (Jones, 2013). After recording the results from the three successful trials for each participant, the mean value over the three trials was calculated and reported.

2.2.4 Force-Time Data Analysis

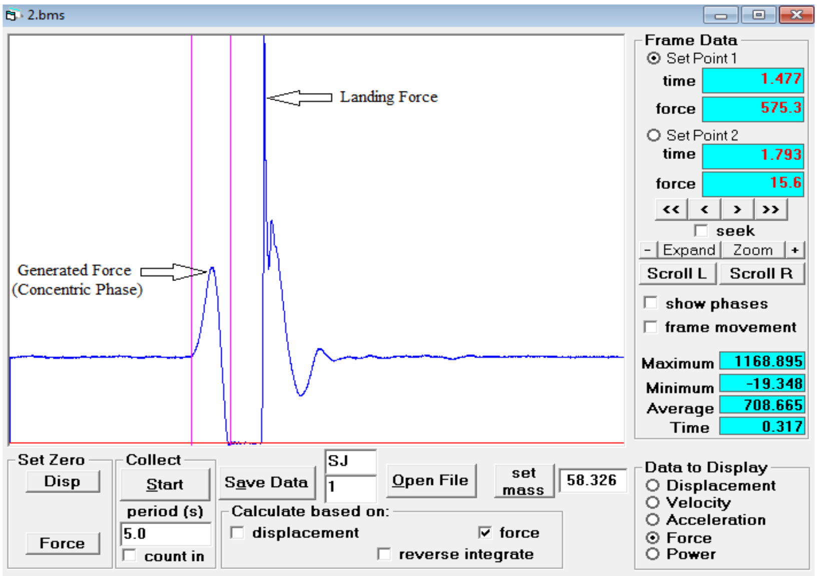
All force data was processed and analysed using Ballistic Measurement System (BMS) Software (v2012.3.7). Only related force data were normalised to body weight after analysing all of the test variables (force related variables were peak RFD, peak force, peak power, impulse at 100 ms, 200 ms, 250 ms, and 300 ms) by dividing the final results by body weight. The concentric phase was the only phase analysed throughout all of the tests. After recording results from the three successful trials for each participant, the mean value over the three trials was calculated and reported. For the 10 consecutive hops test, the mean value of the resultant 10 successful hops from each trial was calculated, and then the final mean value of the three trials was reported. It was taken into consideration that the first provided force in the 10 hops force-time data was not analysed, as it was a countermovement hop which had different force-time characteristics to the rest of the nine hops. The software identifies the onset of movement with a threshold set at 40 N. A detailed analysis of each of the individual tests is explained in the following sections:

2.2.4.1 Squat Hop Data Analysis

The data resulting from the data collection did not include eccentric phase in force-time curve (concentric phase only) (see Figure 2.13). The onset of movement for the concentric phase in the squat hop test was set with thresholds of movement at 40 N. The instants of take-off and touchdown were defined as the instants at which vertical force had fallen below and above, respectively, a threshold equal to five times the standard deviation of the residual force which was calculated during the first 200 milliseconds of flight phase of the hop (i.e. when the force plate was unloaded). The 200 millisecond timeframe for this residual force threshold calculation is in line with previous suggestions (Moir, 2008). The dependant variables analysed included peak force, peak velocity, peak power, and peak instantaneous RFD. Dependant variables were calculated from the force-time data during the concentric phase, as described below.

Peak force was identified as the highest force achieved over the force-time trace during the activity prior to take off. Centre of mass velocity for squat hop was determined by dividing vertical force data (minus body weight) by body mass and then integrating the product using the trapezoid rule (Moir, 2008). Instantaneous power was then calculated by multiplying vertical force and velocity data at each time point, with the highest resultant value representing peak power.

Peak instantaneous RFD was calculated as the difference between two adjacent force samples divided by the intersample time interval 0.00167 second (1 / 600 Hz = 0.00167) in order to calculate the instantaneous RFD. The peak instantaneous RFD was calculated as the maximum value achieved over the first derivative of the force-time trace.



● Set Point 1
time 1.477
force 575.3
○ Set Point 2
time 1.793
force 15.6
☐ seek
☐ show phases
☐ frame movement
Maximum 1168.895
Minimum -19.348
Average 708.665
Time 0.317
SJ
1
58.326
period (s) 5.0
☐ count in
Calculate based on:
☐ displacement ☑ force
☐ reverse integrate
○ Displacement
○ Velocity
○ Acceleration
● Force
○ Power

Figure 2.13. Illustrates the analyses of the squat hop data

2.2.4.2 Countermovement Hop Data Analysis

The final collected data on force generation included the eccentric and concentric work phases in a force-time curve. In CMJ, there is an eccentric action of agonist muscles followed by a concentric action, and jump performance results, generally, from the use of the elastic energy generated in the stretch shortening cycle (SSC) (Pupo et al., 2012). The unweighting phase is considered to occur between the onset of countermovement hop movement and the instant of peak negative centre of mass velocity (which is equal to body weight). The eccentric phase of the countermovement hop is defined as occurring between the instants of peak negative centre of mass velocity and zero centre of mass velocity. The onset of movement for the concentric phase in the countermovement hop test was set with thresholds of movement at 40 N. The instants of take-off and touchdown were defined as the instants at which vertical force had fallen below and above, respectively, a threshold equal to five times the standard deviation of the residual force, which was calculated during the first 200 milliseconds of the flight phase of the hop (i.e. when the force plate was unloaded). The 200 millisecond timeframe of this residual force threshold calculation is in line with previous suggestions (Moir, 2008).

The dependant variables analysed included peak force, peak velocity, peak power, and peak instantaneous RFD during the concentric phase. Dependant variables were calculated from the force-time data, as explained above in the squat hop data analysis.

2.2.4.3 Ten Consecutive Hops Data Analysis

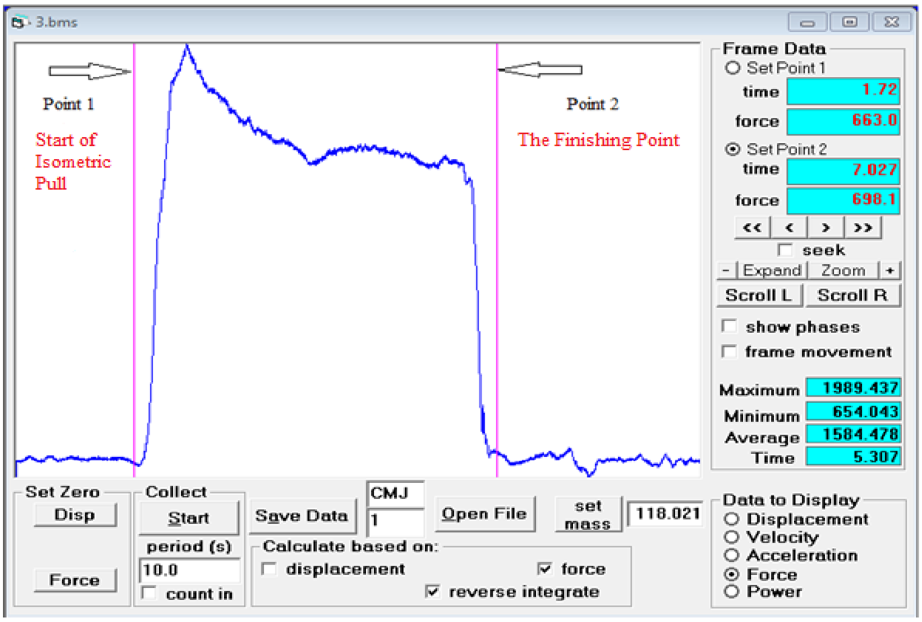
The final data collected for the ten consecutive force generations included ten eccentric and concentric phases in a force-time curve. Here, the analysis was done over the proportion of the whole phase (e.g. concentric phase only) for each of the individual forces, and not for the overall phase, which included the landing force and eccentric phase. The unweighting phase was considered to have occurred between the peak landing vertical force and the instant of peak negative centre of mass velocity (which is equal to body weight). The eccentric phase was defined as occurring between the instants of peak negative centre of mass velocity and zero centre of mass velocity. The onset of movement for the concentric phase was set with thresholds of movement at 40 N. The instants of take-off and touchdown were defined as the instants at which vertical force had fallen below and above, respectively, a threshold equal to five times the standard deviation of the residual force, which was calculated during the first 200 milliseconds of flight phase of the hop (i.e. when the force plate was unloaded). The 200 millisecond timeframe of this residual force threshold calculation is in line with previous suggestions (Moir, 2008).

The dependant variables analysed included peak force, peak velocity, peak power, and peak instantaneous RFD during the concentric phase. Dependant variables were calculated from the force-time data, as explained above in the squat hop data analysis.

2.2.4.4 Isometric Mid-Thigh Pull Data Analysis

The final collected force generation data included only the isometric phase in a force-time curve. In this test, peak force was known as the greatest recorded instantaneous force on the body during an IMTP test, so the peak force was performed at the beginning of the trial, otherwise it was considered a failed trial (see Figure 2.14). The start of each trial was determined as increase in force greater than 40 N. The dependant variables analysed included peak force, peak instantaneous RFD, impulse 0-100 milliseconds (ms), impulse 0-200 ms, impulse 0-250 ms, and impulse 0-300 ms. Dependant variables were calculated from the force-time data, as described below:

Peak force and peak instantaneous RFD data were calculated from the force-time data as previously explained above in the squat hop data analysis. For the calculation of impulse at 100, 200, 250, and 300 ms, the vertical force-time curve was integrated over 100-, 200-, 250- and 300-millisecond windows from the onset of force production, when the vertical force increased above a threshold of 40 N, (Comfort et al., 2015).



○ Set Point 1
time 1.72
force 663.0
● Set Point 2
time 7.027
force 698.1
☐ seek
☐ show phases
☐ frame movement
Maximum 1989.437
Minimum 654.043
Average 1584.478
Time 5.307
CMJ
1
set mass 118.021
period (s) 10.0
☐ count in
Calculate based on:
☐ displacement
☑ force
☑ reverse integrate
Data to Display
○ Displacement
○ Velocity
○ Acceleration
● Force
○ Power

Figure 2.14. Illustrates the analyses of the IMTP data

2.2.5 Isokinetic Muscle Strength Data Analysis

Muscle strength data was processed and analysed using Biodex System 4 with associated Software (Biodex Medical Systems, Inc, Shirley, New York, USA). After recording the results of the three trials for each participant, the mean value over the three trials was calculated and reported. The outcome measures for strength tests were peak torque, peak torque to body weight, and the total work to body weight in concentric and eccentric muscle actions. An explanation of these outcome measures is set out below:

1. Peak torque: this was the highest muscular force output at any time during the repetition of concentric/eccentric muscle contraction trials (the highest point on the curve). This was determined within each repetition for the entire set. The test angles for the peak torque were as explained earlier in the isokinetic muscle test for each of the individual muscle tests.
2. Peak torque to body weight: this was the peak torque value normalised to bodyweight and represented as a percentage (%). The test angles for the peak torque to body weight were as explained earlier in the isokinetic muscle test for each of the individual muscle tests.
3. Work to body weight: this was a ratio presented as a percentage (%) of the maximum work repetition to the participant's body weight, and the calculation was as follows:

Work = torque multiplied by distance produced in the entire ROM.

Total work to body weight = a percentage of the maximum work repetition to the participant's body weight.

The test angles for the total work to body weight were as explained earlier in the isokinetic muscle test for each of the individual muscle tests.

2.3 Force and Isokinetic Tests Chosen Variables

The reasons behind choosing the force and isokinetic dependant variables used in the current study are explained below:

2.3.1 Force Generation Dependant Variables

2.3.1.1 Peak Instantaneous RFD

The reasons behind choosing the peak instantaneous RFD variable is because of the reliability of the data from the RFD in the study by Mizuguchi et al. (2015), which during CMJ was good (0.78). Furthermore, the reliability of the peak RFD during isometric mid-thigh clean pulls has been investigated by Kawamori et al. (2006), and showed an excellent ICC of 0.96. The same study investigated the relationship between dynamic Peak RFD and vertical jump performance and demonstrated a strong correlation between them.

Angelozzi et al. (2012) investigated the RFD to 30% (RFD30), 50% (RFD50), and 90% (RFD90) of maximal voluntary isometric contraction (MVIC) as an additional outcome measure to determine readiness to return to sport after ACL reconstruction. Forty-five professional male football players who underwent an ACL surgery were recruited. The KT1000 instrumented arthrometer was used at pre-reconstruction, six months, and at 12 months after ACL surgery. MVIC, RFD30, RFD50, and RFD90 testing was done pre-injury, as part of a standard pre-season evaluation, and at six months and 12 months post-ACL reconstruction. The results from this study suggest that RFD criteria may be a useful adjunct outcome measure for the decision to return to sports following ACL reconstruction. Moreover, the reason behind choosing the peak RFD in the current study, rather than the average RFD, is because the average RFD failed to meet the reliability standards set in the study by Haff et al. (2015). Therefore, and from the above explanations, it seems to be that peak RFD value is a really important factor that needed to be considered in this study, as it demonstrated very high reliability during CMJ tasks. Additionally, peak RFD was previously considered to be related to ACL reconstructed patients to determine readiness to return to sport after ACL surgery during MVIC, and also peak RFD was related to athletic performance, especially during vertical jump performance tasks.

2.3.1.2 Peak Force

The reasons behind choosing the PF variable is because the reliability of the data on peak force in the study by Moir et al. (2005) during SJ was very high (0.96), and in the study by Sheppard et al. (2008), CMJ peak force reliability was also very high (0.96). Furthermore, the reliability of the PF during isometric mid-thigh clean pulls has been investigated by Kawamori et al. (2006) and showed excellent ICC of 0.97. The same study investigated the relationship between the isometric PF and vertical jump performance and demonstrated a strong correlation between them.

In addition, the results of the study by Kawamori et al. (2006) show that PF values of IMTP and peak RFD values of dynamic mid-thigh pull are strongly correlated to vertical jump performance, especially PF values of IMTP being strongly correlated to the PF values of both CMJ and SJ. Therefore, and from above explanations, it seems to be that PF value is a really important factor that needed to be considered in this study, as it has demonstrated very high reliability in different studies using different methodologies, so it is a very reliable variable when examining different jumping tasks. Also, PF was previously considered to be related to athletic performance, especially during vertical jump activities.

2.3.1.3 Peak Power

The reasons behind choosing the peak power variable are because the reliability of the data on peak power in the study by Moir et al. (2005) during SJ is very high (0.97), and in the study by Sheppard et al. (2008), CMJ peak power reliability was also very high (0.80). The results of the study by Kawamori et al. (2006) indicate that peak power values of hop performance during CMJ and SJ are strongly correlated with isometric and dynamic med-thigh pull force characteristics, especially PF values of IMTP, which had the strongest correlation with the peak power values of CMJ and SJ. Therefore, and from the above explanations, it seems to be that peak power value is a really important factor that needs to be considered in this study, as it has demonstrated very high reliability in different studies using different methodologies, so it is a very reliable variable when examining different jumping tasks. In addition, peak power was previously considered to be related to athletic performance, especially during SJ and CMJ activities.

2.3.1.4 Peak Velocity

The reasons behind choosing the peak velocity variable is because the reliability of the data on takeoff velocity in the study by Moir et al. (2005) study during SJ was very high (0.93). Another study investigated the reliability of peak velocity during 30 seconds of continuous squat jumps using 30% of one repetition maximum, and the results demonstrated excellent ICCs ranging between 0.80 and 0.96 (Alemany et al., 2005).

Apart from reporting excellent reliability results for peak velocity during different athletic tasks, concurrent vertical velocity was used previously in the literature in order to calculate instantaneous power by multiplying vertical force by concurrent vertical velocity (Kawamori et al., 2006). Therefore, it seems that peak velocity is an important factor that indicates jump performance, as it has demonstrated very high reliability previously, and it is also considered to be related to athletic performance, especially during dynamic activities (to calculate instantaneous power).

2.3.1.5 Impulses 0-100, 200, 250, and 300 ms

The reasons behind choosing the impulses variables from 100 to 300 ms during the IMTP is because it has been reported by Comfort et al. (2015) that impulses measured at 100, 200, and 300 ms provide higher within- and between-sessions reliability than peak RFD, and therefore evaluation of impulse would be preferable. Impulse measures are important, as they have been reported by Sleivert and Taingahue, (2004), Wilson et al. (1995), and Tidow, (1990) to be excellent predictors of athletic performance if the timeframe for force application is generally equal to or less than 300 ms. Therefore, it seems that impulses from 100 to 300 ms are important variables that indicate IMTP performance, as they have demonstrated very high reliability previously, and they are also considered to be related to athletic performance.

2.3.2 Isokinetic Muscle Strength Dependant Variables

2.3.2.1 Peak Torque, Peak Torque to Body Weight, and Total Work to Body Weight

The reasons behind choosing the peak torque, peak torque to body weight, and total work to body weight variables during isokinetic muscle testing is because Keays et al. (2003) assessed the relationship between knee muscle strength (peak torque) and functional stability and single-leg hop performance in pre- and post-ACL surgery participants at a speed of 60°/sec. The results demonstrate that there was a relationship between quadriceps muscle strength (peak torque) and functional stability. Additionally, another relationship was found between quadriceps muscle strength (peak torque) and single-leg hop performance both pre- and post-surgery. Another study investigated the importance of muscle strength in landing (Jacobs and Mattacola, 2005) and reported that women with greater eccentric hip-abductor peak torque value demonstrated lower peak knee-valgus angles during landing.

Another study by Greenberger and Paterno (1995) was carried out to examine the relationship between quadriceps muscle strength and functional performance using a one-legged hop test for distance. This study reports a correlation between muscle peak torque and distance hopped for both the dominant leg and the non-dominant leg. In addition, Pincivero et al. (1997) reported a relationship between a single-leg hop distance test and isokinetic variables (peak torque, peak torque to body weight, and total work) for the hamstring and quadriceps muscles of both limbs in healthy participants, with a test speed of 60 degrees/sec ranging between $r = 0.33$ and 0.69.

Regarding the reliability of the isokinetic variables, Maffiuletti et al. (2007) evaluated the test re-test reliability of isokinetic assessments of the knee extensor and the flexor muscles using the Con-Trex isokinetic dynamometer for maximal strength (isokinetic peak torque and work). For both the knee extensor and the flexor muscle groups, all strength data were reliable. The highest reliability was recorded for concentric peak torque of the knee extensor muscles (ICC = 0.99); insufficient to moderate ICC for the knee flexor muscles ranged between 0.78-0.81. Another reliability study by Pincivero et al. (1997) indicates the extension and flexion knee muscles' reliability during concentric manoeuvres at a speed of 60˚/sec for the peak torque, peak torque to body weight, and the total work, ranging from 0.76 to 0.97.

Therefore, and from the previous explanations, it seems that isokinetic variables (peak torque, peak torque to body weight, and total work) are important, as they have demonstrated very high reliability previously, and they are also considered to be related to athletic activities, especially hop performance.

Chapter (3)

Test Re-Test Reliability of Different Test Variables During a Series of Athletic Tasks, and Establishing the Measurement Error

3 Chapter 3: Test Re-Test Reliability of Different Test Variables During a Series of Athletic Tasks, and Establishing the Measurement Error

3.1 Aims

1. Examine the within- and between-days reliability of five tests, which are; hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic muscle tests.

2. Establish standard measurement error (%SEM) during these tasks in recreational healthy participants.

3.2 Background

In many sports, athletes are required to transfer horizontally along a playing surface in a very quick and efficient manner, and for this reason, athletes usually participate in training and rehabilitation programs that improve their ability to move and hop horizontally (Ross et al., 2012). To evaluate an athlete's horizontal movement capabilities better, Noyes et al. (1991) developed the single hop for distance and the crossover hop for distance tests that assess horizontal hopping capabilities. Single-leg horizontal hop tests have demonstrated acceptable reliability (Booher et al., 1993; Bolgla and Keskula, 1997). Although single-leg horizontal hop tests have been used in assessing strength and power (Decarlo and Sell, 1997), they are commonly used in field or clinical settings to monitor the progress made in a training/rehabilitation program or to determine the level of recovery after lower limb injury or surgery.

Isokinetic dynamometry is a reliable tool and is considered the gold standard for evaluating muscle strength, enabling a detailed assessment of muscle function during the full range of motion by providing equal opposing torque at set testing speeds (Jones and Stratton, 2000). Isokinetic dynamometry is widely used and considered a safe tool to be used in clinical practice and research (Tsiros et al., 2011). The same authors state that the knee flexor and extensor muscles are commonly investigated as they are prime movers for many functional activities. It has been demonstrated that these muscles play a key role in stabilising the knee joint and helping to absorb the shock during gait by attenuating ground reaction forces (Mikesky et al., 2000).

Force-time curve analysis has been used previously to assess skeletal muscle function (Ryushi et al., 1988). Force-time characteristics such as maximum RFD, PF, peak power, peak velocity, and the impulses 0-100, 200, 250, 300 ms have been widely used to investigate the reliability of the functional performance during different tasks such as SJ (Moir et al., 2005), CMJ (Mizuguchi et al., 2015; Sheppard et al., 2008), and IMTP (Comfort et al., 2015). In addition, the force platform used in balance tests is, like any other measurement tool, subject to measurement errors. However, there is agreement in the literature that using a force plate is a reliable form of measurement for both COP and TTS parameters (Birmingham, 2000; Ross et al., 2005). The reliability of COP measurements has been widely investigated using different protocols and parameters (Birmingham, 2000). The TTS has also been utilised to examine stability when completing functional hop procedures, TTS measurement reliability has been investigated in the study by Ross et al. (2005).

Furthermore, many screening tests have been used in the literature to evaluate dynamic knee valgus (Munro et al., 2012). These tests involved the SLS (Willson and Davis, 2008; Willson et al., 2006; Zeller et al., 2003), drop vertical jump (Hewett et al., 2005; Noyes et al., 2005; Herrington and Munro, 2010), single-leg landing (Lawrence et al., 2008), and drop landing (Decker et al., 2003). In clinical research, either 3-D or 2-D motion-analysis systems are available for measuring functional movement. 3-D has been considered the gold-standard measurement tool for gait analysis (Munro et al., 2012). However, 3-D systems are very expensive and require experienced operators, which means that the 2-D systems may be more useful in practice (Munro et al., 2012; Rowe, 1999). 2-D analysis has been used to evaluate knee-valgus angle in healthy, athletic, and injured populations (Willson et al., 2006; Noyes et al., 2005). The reliability studies of FPPA using 2-D analysis with ICC have been investigated and reported using different screening tasks (Munro et al., 2012; Willson et al., 2006).

The reliability of all of the above mentioned tests has been reported and explained in detail in the literature review chapter. The reliability of the data shows different variations and methods, and therefore, the purpose of this study is to investigate the reliability of all the tests which were included in the main study. These tests are hop test, 2-D FPPA, balance test, force generation test, and muscle strength test. This may inform rehabilitation strategies and help to ensure appropriate procedure prior to returning players to their sport, which may involve various types of rehabilitation programs such as eccentric strengthening of the leg muscles, improving overall limb balance, and improving knee kinematics in landing protocol.

3.3 Study Hypotheses (H)

Five hypotheses were formulated based on the review of the literature:

H1. There is agreement between repeated measurement scores examined in both within-day and between-days tests for two hop tests, which are single-leg horizontal hop for distance and crossover hop tests.

H2. There is agreement between repeated measurement scores examined in both within-day and between-days tests for 2-D FPPA during maximum knee flexion position in both SLS and single-leg horizontal hop land tests.

H3. There is agreement between repeated measurement scores examined in both within-day and between-days tests for balance performance in both static and dynamic tasks.

H4. There is agreement between repeated measurement scores examined in both within-day and between-days tests for force generation tests in different dynamic hop activities and an IMTP test.

H5. There is agreement between repeated measurement scores examined in both within-day and between-days tests for isokinetic muscle testing, which includes quadriceps, hamstring, ankle plantar flexor, and hip extensor muscles all in during concentric and eccentric muscle actions.

3.4 Methods

3.4.1 Participants

Twelve recreationally active healthy students met the study's inclusion criteria and agreed to take part in this study. They were undergraduate and postgraduate students recruited from the Applied Sports Science and Physiotherapy programmes, as well as Sport Rehabilitation courses, and consisted of eight males and four females (age 34.16 ± 3.05 years; height 170 ± 6.47 cm; and mass 82.08 ± 15.94 kg). The subjects were physically active and had performed at least 30 minutes of physical activity three times a week on a regular basis over the last six months (Munro and Herrington, 2011). Table 3.1 below presents the descriptive statistics for the characteristics of these participants. Mean and standard deviation for the age, height and weight of the participants are also summarised.

Table 3.1. Demographic data for all participants (N=12)

	Range		**Mean**	**Standard Deviation**
	Minimum	Maximum		
Age (Years)	29	41	34.17	3.05
Height (Centimetres)	157	178	170.83	6.48
Weight (Kilograms)	56	116	82.08	15.94

3.4.1.1 Inclusion Criteria

1. Healthy participants able to stand, bend their legs, hop, and land independently.
2. Over 18 years of age.
3. Able to give informed consent.

3.4.1.2 Exclusion Criteria

1. Subjects with pathology or pain in a lower limb affecting standing, bending legs, and hopping or landing ability.
2. Lower-limb injury during the last year.
3. Lower-limb deformities.
4. Unable to give informed consent.

Before participation, each subject read the information sheet and signed the informed consent form which has been approved by the Research, Innovation and Academic Engagement Ethical Approval Panel at the University of Salford (Appendix A).

3.4.2 Facilities and Resources

The experimental procedures were conducted in the Human Performance Laboratory at the University of Salford. All equipment required for the research was already available within the Directorate of Sport. Therefore, no funding was needed for the testing. The study analysis and results remained anonymous and confidential and only able to be accessed by the researcher.

3.4.3 Procedure

For each participant, the measurements of the performance of all five different tests were taken for both legs individually. Subjects were asked to wear the same training shoes each time they attended, with these shoes being the ones they wear the majority of the time for their training activities to avoid any differences in the landing surfaces that may occur as a result of different shoes (Munro and Herrington, 2011). The participants took part in two experimental tests on one day (with one hour between each testing session), and another seven days later (Birmingham, 2000) at the same time as the first session. A two minutes rest period was given in between each test (Corriveau et al., 2000), with half a minute rest between trials. All subjects were asked not to perform any exercise in the 24 hours prior to testing day, and also not to eat one hour before the testing sessions (Munro and Herrington, 2011).

The tests were:

1. Hop Tests:
A. Single-leg horizontal hop for distance test.
B. Single-leg crossover hop test.
2. 2-D FPPA:
A. SLS.
B. Single-leg horizontal hop for distance.
3. Balance Tests:
A. Straight leg (sway area).
B. Bent (30˚) leg (sway area).
C. Single-leg horizontal hop land (TTS).
4. Force Generation Tests:
A. Squat hop.
B. Countermovement hop.
C. Ten consecutive hops.
D. Isometric mid-thigh pull.
5. Isokinetic Muscle Tests:
A. Quadriceps muscle.
B. Hamstring muscle.
C. Ankle plantar flexor muscles.
D. Hip extensor muscles.

The procedure has previously been mentioned and explained in detail in the methods chapter (Chapter 2).

3.4.4 Statistical Analysis

Statistical analysis was performed using Statistical Package for Social Sciences (SPSS) software (v. 21, SPSS Inc., Chicago, IL). The mean value of the three measures (trials) for each session 1, 2, and 3 was calculated to find out the reliability between session 1 and 2 (within day) and between session 1 and 3 (between days). Intra-class correlation coefficients (ICC), model 3.3, were used to evaluate relative reliability. Since the principal researcher performed all the measurements, these results cannot be generalisable to other raters, thus the two-way-mixed model was utilised (Shrout and Fleiss, 1979). The first number shows the use of the two-way-mixed model of ICC, whereas the second number indicates the use of an average measurement (Portney & Watkins, 2009). The levels of ICC were determined according to the criteria presented in Table 3.2 (Coppieters et al., 2002).

Table 3.2. The classification of ICC values

ICC Value	**Classification**
Less than 0.40	Poor
0.40 – 0.75	Fair
0.75 – 0.90	Good
More than 0.90	Excellent

The ICC seems to be easy to read; the closer the value to one, the greater the reliability is. However, ICC alone cannot provide a full picture of reliability and should be accompanied by confidence intervals (CI). Moreover, ICC cannot provide any information about the amount of disagreement between measurements. A high ICC with low standard error of measurement (SEM) indicates good reliability of a measure. Therefore, SEM was used in conjunction with ICC and a CI of 95% to establish random error scores.

SEM calculations were performed using the formula:

SD (pooled) × $\sqrt{1}$- ICC (Thomas et al., 2005).

The SEM then expressed in percentage for each test to be as %SEM using the formula:

SEM / Mean (both sessions) × 100 = %SEM

Moreover, repeated measures ANOVA were performed to determine if significant differences occurred between testing sessions with Bonferroni post-hoc analysis used for pairwise comparisons. All data were tested for normality using a Shapiro-Wilk test; values were not normally distributed if they were equal to or less than ≤ 0.05 (for full details about these results please see Appendix B). Force data was normalised to body weight, and hop data was normalised to leg length, as explained in depth in the data processing and analysis section in the methods chapter (Chapter 2).

3.5 Results

Tables 3.3 and 3.4 contain means and standard deviation for each individual session (one, two, and three) for all tests, and Table 3.5 shows the non-normalised hop data.

Table 3.3. Contains means and standard deviation for each session for hop tests, 2-D FPPA tests, balance tests, and force tests

Tests			Right Leg			Left Leg		
			Session 1	Session 2	Session 3	Session 1	Session 2	Session 3
			Mean ± Sd	Mean ± Sd	Mean ± Sd	Mean ± Sd	Mean ± Sd	Mean ± Sd
Hop	Horizontal Hop for Distance (%)		119.8 (28.6)	107 (19.8)	110.4 (29.9)	119.5 (26.7)	114.1 (24.9)	107.3 (21.1)
	Crossover hop (%)		325.9 (75.5)	315.3 (74.2)	321.4 (74.6)	324.4 (69.9)	310.3 (67.1)	319.2 (72.5)
2D	Squat (˚)		8.2 (4.2)	7.4 (4.1)	8.6 (5)	8.2 (4.8)	9 (4.9)	7.9 (4.3)
	Hop Land (˚)		8.1 (4.3)	8.8 (5)	7.1 (4)	7.8 (3.9)	8.4 (4.6)	7.5 (4.2)
Balance	Straight Leg (cm^2)		1.371 (0.251)	1.338 (0.248)	1.388 (0.207)	1.533 (0.274)	1.527 (0.267)	1.543 (0.272)
	Bent Leg (cm^2)		1.393 (0.315)	1.390 (0.363)	1.393 (0.330)	1.517 (0.389)	1.551 (0.414)	1.523 (0.399)
	Hop Land (TTS) (sec)		0.395 (0.065)	0.4 (0.061)	0.395 (0.063)	0.404 (0.061)	0.399 (0.058)	0.403 (0.060)
Force	Squat Hop	Max RFD (N·sec/kg)	56.9 (15.2)	57.2 (16.4)	58.1 (16.2)	62.3 (16.6)	61.5 (16.2)	60.3 (14)
		Peak Force (N/kg)	17.3 (1.8)	16.9 (1.9)	17.2 (1.6)	18.3 (3.8)	18 (3.5)	18.3 (3.8)
		Peak Power (W/kg)	21 (3.1)	20.8 (3)	21 (3)	22.4 (6.2)	22 (5.9)	22.3 (5.9)
		Peak Velocity (m/s)	1.478 (0.191)	1.483 (0.185)	1.499 (0.177)	1.552 (0.360)	1.549 (0.275)	1.545 (0.297)
Force	Countermovement Hop	Max RFD (N·sec/kg)	82 (20.6)	81.1 (21.3)	81.7 (22)	71.4 (23.3)	72 (23.2)	69.6 (24.2)
		Peak Force (N/kg)	18.9 (3)	18.7 (2.6)	18.9 (3.2)	18.7 (3.5)	18.3 (3.3)	18.5 (3.3)
		Peak Power (W/kg)	23.8 (4.6)	23.6 (4.7)	23.9 (4.7)	23.8 (5.7)	23.7 (5.8)	23.7 (5.5)
		Peak Velocity (m/s)	1.610 (0.2)	1.592 (0.227)	1.616 (0.219)	1.662 (0.239)	1.658 (0.263)	1.646 (0.227)
Force	10 Consecutive Hops	Max RFD (N·sec/kg)	83.7 (25.8)	82.9 (23.8)	85.1 (25.1)	84.3 (22.2)	83.0 (21.8)	85.4 (22.5)
		Peak Force (N/kg)	16.5 (4.3)	16.6 (4.1)	16.9 (4.3)	16.6 (4)	16.5 (4)	16.7 (4.1)
		Peak Power (W/kg)	18.8 (4.2)	18.6 (4.2)	19.2 (4.3)	19.2 (4.5)	18.6 (4.6)	19.2 (4.6)
		Peak Velocity (m/s)	1.356 (0.211)	1.347 (0.194)	1.373 (0.225)	1.211 (0.230)	1.174 (0.219)	1.235 (0.215)
Force	Isometric Pull	Max RFD (N·sec/kg)	36.8 (10.7)	36.4 (10.4)	36.9 (10.8)	35.3 (8)	36.0 (10.5)	36.4 (10.1)
		Peak Force (N/kg)	17.8 (3.3)	17.9 (3.3)	17.7 (3.3)	17.9 (3.5)	17.9 (3.6)	18.1 (3.4)
		Impulse 0-100 ms (Ns/kg)	0.996 (0.019)	0.998 (0.029)	0.993 (0.042)	0.993 (0.027)	0.996 (0.021)	1.005 (0.036)
		Impulse 0-200 ms (Ns/kg)	1.975 (0.030)	1.974 (0.062)	1.952 (0.083)	1.981 (0.051)	1.980 (0.046)	1.994 (0.036)
		Impulse 0-250 ms (Ns/kg)	2.467 (0.041)	2.479 (0.053)	2.469 (0.06)	2.475 (0.061)	2.467 (0.051)	2.481 (0.053)
		Impulse 0-300 ms (Ns/kg)	2.966 (0.064)	2.985 (0.088)	2.980 (0.063)	2.974 (0.065)	2.959 (0.056)	2.974 (0.073)

(Sd) Standard deviation

Table 3.4. Contains means and standard deviation for each session for isokinetic muscle test

Tests				**Right Leg**			**Left Leg**		
				Session 1	Session 2	Session 3	Session 1	Session 2	Session 3
				Mean ± Sd	Mean ± Sd	Mean ± Sd	Mean ± Sd	Mean ± Sd	Mean ± Sd
Isokinetic	Quadriceps	Peak TQ (N·m)	Concentric	182.3 (63.8)	184.4 (67.9)	186.4 (64.4)	182.8 (65)	182.4 (72.6)	186.3 (69.8)
			Eccentric	216.4 (76.9)	216.7 (77.9)	221 (76.3)	213.9 (69.8)	216.7 (69)	216.4 (68.2)
		Pk TQ/BW (%)	Concentric	214.2 (80)	212.6 (79.1)	215.1 (81)	219.8 (82.2)	217.9 (83)	223.5 (85.5)
			Eccentric	257.1 (92.9)	257.8 (83.7)	261.2 (91.8)	255.4 (83.5)	265.9 (84.4)	269.5 (87.1)
		Work/BW (%)	Concentric	112.6 (29.3)	110.7 (29)	113.3 (29.8)	110.8 (30.6)	119 (33.6)	121 (37.6)
			Eccentric	151.1 (47.1)	151.8 (47)	148.5 (49.3)	155.2 (48.8)	149.9 (51)	152.8 (49.9)
Isokinetic	Hamstring	Peak TQ (N·m)	Concentric	130.7 (18.9)	127.6 (19.7)	128.7 (19)	130.6 (23.7)	132 (22.7)	132.6 (22.7)
			Eccentric	133.3 (21.6)	132.5 (20.9)	134.7 (21.4)	135.6 (25)	136.3 (24.8)	138.6 (23.3)
		Pk TQ/BW (%)	Concentric	152.5 (31.3)	151.5 (29.9)	154.9 (31.4)	155 (25.3)	150.7 (26.1)	155.9 (29)
			Eccentric	158.2 (26.9)	157.1 (26.5)	160.5 (26.9)	159.9 (31.8)	159.2 (31)	161 (32)
		Work/BW (%)	Concentric	96.2 (28.1)	94.7 (24.8)	99.5 (27.1)	104.9 (28.7)	104 (32.5)	109.5 (31.8)
			Eccentric	116 (23.7)	113.7 (23.8)	117.6 (22.8)	116.6 (21.8)	115.1 (22.1)	118.9 (23.3)
Isokinetic	Ankle Plantarflexors	Peak TQ (N·m)	Concentric	155.4 (52)	154.5 (49.8)	156.8 (51.2)	148.4 (48.4)	148.4 (46.7)	151.5 (46.2)
			Eccentric	183.5 (53.5)	183.2 (53.5)	183.7 (51.1)	180.3 (49.4)	176.4 (45.8)	181.6 (47)
		Pk TQ/BW (%)	Concentric	183.8 (60.1)	182.9 (62.9)	185.7 (58.8)	177.2 (57.8)	172.5 (57.4)	177.6 (57.6)
			Eccentric	211.2 (65)	211.4 (66.1)	214.2 (65.5)	209 (61.8)	205.9 (61.8)	208.7 (63.1)
		Work/BW (%)	Concentric	62.5 (31.1)	61.9 (32.2)	63.4 (30)	59.7 (29)	57.7 (26)	58.8 (29)
			Eccentric	89.4 (34.7)	88.1 (32.3)	90.3 (32.7)	86.5 (33.6)	83.8 (33.9)	83.5 (33.4)
Isokinetic	Hip Extensors	Peak TQ (N·m)	Concentric	193.9 (60.2)	193.7 (60.6)	193.9 (59.4)	186.8 (57.5)	184.4 (56)	187.8 (59)
			Eccentric	209.6 (55.4)	207.8 (55.1)	211.3 (54.3)	201.7 (56.2)	201.7 (58.6)	202.8 (57)
		Pk TQ/BW (%)	Concentric	222 (67.1)	220.1 (69.7)	220.6 (65.5)	214.4 (63)	212.8 (63.7)	217 (64.5)
			Eccentric	244.8 (65.9)	242.8 (67.8)	248 (67.2)	235.8 (67.8)	228.6 (65.4)	235.3 (69.1)
		Work/BW (%)	Concentric	98.5 (30.2)	99.1 (29.9)	100.8 (30.2)	96.6 (31.2)	95.1 (30.2)	97.1 (31.4)
			Eccentric	174 (53.1)	172.1 (52.5)	176.2 (52.7)	168.4 (51)	165.6 (51.3)	170.8 (51.7)

(Peak TQ) Peak torque; (Pk TQ/BW) Peak torque to body weight;

(Work/BW) Work to body weight; (Sd) Standard deviation

Table 3.5. Contains mean and standard deviation for non-normalised hop data for both hop tests across all sessions

Test	**Right Leg**			**Left Leg**		
	Session 1	Session 2	Session 3	Session 1	Session 2	Session 3
	Mean ± Sd	Mean ± Sd	Mean ± Sd	Mean ± Sd	Mean ± Sd	Mean ± Sd
Single-leg hop for distance (cm)	101.5 (24.8)	90.7 (17.4)	93.6 (26)	101.4 (23.5)	96.8 (21.6)	91.2 (19.5)
Crossover hop for distance (cm)	275.8 (63.3)	266.6 (61.4)	271.8 (62.1)	274.6 (59)	262.7 (56.9)	270.3 (61.1)

(Sd) Standard deviation

Tables 3.6 and 3.7 contain ICCs with (95% CI), while Tables 3.8 and 3.9 contain means and %SEM values for all the tests, which were hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic muscle tests. For the hop test results, the ICC range value for the within-day results was slightly lower (0.87-0.99) than the between-days results (0.90-0.99). The ICC range value of the 2-D FPPA test for within-day was also slightly lower (0.95-0.97) than the between-days values (0.96-0.98). For the balance tests, the ICC range value for the within-day tests was exactly the same as the between-days results (0.95-0.99). The ICC range value of force tests was higher for within-day (0.54-0.99) than the between-days results (0.49-0.99). Finally, the ICC range values of isokinetic muscle test were excellent in both within-day (0.94-0.99) and between-days results (0.93-0.99). Therefore, most of the tests used had an excellent range of reliability (0.87-0.99), apart from the range of the force test reliability results which demonstrated a fair to excellent range value of 0.49-0.99.

The within- and between-day %SEM values for hop tests during single hop distance ranged between (4.9% - 7.7%) and in crossover hop for distance they ranged between (2.2% - 2.3%). Furthermore, the within- and between-day %SEM values for 2-D FPPA tests during squats ranged between (7.7% - 9.7%) and in the single hop for distance test ranged between (9.5% - 11.8%). Moreover, the within- and between-day %SEM values for balance tests with straight leg ranged between (2.6% - 4.4%), bent leg ranged between (2.2% - 2.6%), and for the single-leg hop test (TTS) were 2.5%. In addition, the within- and between-day %SEM values for force generation tests during the squat hop ranged between (maximum RFD 2.7 - 3.9%, peak force 1.9 - 2.7%, peak power 1.5 - 2.8%, and peak velocity 1.9 - 3.4%); countermovement hop ranged between (maximum RFD 2.6 - 3.4%, peak force 1.5 - 3.2%, peak power 2 - 2.4%, and peak velocity 1.2 - 1.8%); ten consecutive hops ranged between (maximum RFD 2.6 - 3%, peak force 2.4 - 2.6%, peak power 2.2 - 2.4%, and peak velocity 1.5 - 1.7%), and isometric mid-thigh pull ranged between (maximum RFD 2.9 - 5.2%, peak force 1.9 - 2%, impulse 0-100 ms was at 2%, impulse 0-200 ms 1 - 1.5%, impulse 0-250 ms was at 0.81%, and impulse 0-300 ms 0.67 - 1%). Finally, the within- and between-day %SEM values for isokinetic muscle tests during quadriceps muscle tests for both concentric and eccentric muscle action ranged between (peak torque 3.2 - 3.8 %, peak torque to body weight 3.2 - 4.6 %, and work to body weight 2.6 - 7.8 %); the hamstring muscle test for both concentric and eccentric muscle actions ranged between (peak torque 1.6 - 2.5 %, peak torque to body weight 1.7 - 3 %, and work to body weight 2.7 - 4.1 %); the ankle plantar flexors muscle test for both concentric and eccentric muscle action ranged between (peak torque 2.7 - 3.3 %, peak torque to body weight 3 - 3.4 %, and work to body weight 3.7 - 5.6 %), and the hip extensors muscle test for both concentric and eccentric muscle action ranged between (peak torque 2.6 - 3.1 %, peak torque to body weight 2.7 - 3.1 %, and work to body weight 3 - 3.2 %).

Table 3.6. Interclass correlations (ICC) and 95 % confidence intervals (95% CI) for hop tests, 2-D FPPA tests, balance tests, and force tests

Test	ICC (95% CI)			
	Within-day		Between-days	
	Right Leg	Left Leg	Right Leg	Left Leg
Hop Tests				
Single Hop	0.87 (0.28-0.97)	0.95 (0.82-0.99)	0.95 (0.65-0.99)	0.90 (0.16-0.98)
Crossover Hop	0.99 (0.92-0.99)	0.99 (0.59-0.99)	0.99 (0.97-0.99)	0.99 (0.98-0.99)
2-D FPPA Tests				
Hop Land	0.97 (0.88-0.99)	0.95 (0.85-0.99)	0.97 (0.79-0.99)	0.96 (0.85-0.99)
Squatting	0.97 (0.86-0.99)	0.97 (0.89-0.99)	0.98 (0.93-0.99)	0.98 (0.94-0.99)
Balance Tests				
Straight Leg	0.95 (0.82-0.99)	0.98 (0.93-0.99)	0.95 (0.82-0.99)	0.98 (0.93-0.99)
Bent Leg	0.99 (0.95-0.99)	0.99 (0.97-0.99)	0.99 (0.96-0.99)	0.99 (0.98-0.99)
Hop Land	0.99 (0.95-0.99)	0.99 (0.95-0.99)	0.98 (0.94-0.99)	0.99 (0.97-0.99)
Force Tests				
Squat Hop				
Maximum RFD	0.99 (0.97-0.99)	0.99 (0.97-0.99)	0.98 (0.95-0.99)	0.98 (0.93-0.99)
Peak Force	0.97 (0.86-0.99)	0.99 (0.98-0.99)	0.93 (0.74-0.98)	0.99 (0.96-0.99)
Peak Power	0.99 (0.98-0.99)	0.99 (0.99-0.99)	0.99 (0.97-0.99)	0.99 (0.99-0.99)
Peak Vel	0.92 (0.71-0.98)	0.97 (0.90-0.99)	0.93 (0.74-0.98)	0.99 (0.96-0.99)
Countermovement Hop				
Maximum RFD	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.98-0.99)
Peak Force	0.99 (0.98-0.99)	0.98 (0.92-0.99)	0.99 (0.98-0.99)	0.97 (0.90-0.99)
Peak Power	0.99 (0.99-.099)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)
Peak Vel	0.99 (0.96-0.99)	0.99 (0.96-0.99)	0.99 (0.98-0.99)	0.99 (0.97-0.99)
Ten Consecutive Hops				
Maximum RFD	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)
Peak Force	0.99 (0.99-0.99)	0.99 (0.98-0.99)	0.99 (0.97-0.99)	0.99 (0.99-0.99)
Peak Power	0.99 (0.98-0.99)	0.99 (0.95-0.99)	0.99 (0.98-0.99)	0.99 (0.99-0.99)
Peak Vel	0.99 (0.97-0.99)	0.99 (0.87-0.99)	0.99 (0.96-0.99)	0.99 (0.96-0.99)
IMTP				
Maximum RFD	0.99 (0.99-0.99)	0.96 (0.87-0.99)	0.99 (0.99-0.99)	0.97 (0.89-0.99)
Peak Force	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.98-0.99)	0.99 (0.98-0.99)
Impulse 0-100 ms	0.55 (0.20-0.82)	0.54 (0.09-0.77)	0.49 (0.13-0.79)	0.57 (0.23-0.83)
Impulse 0-200 ms	0.80 (0.29-0.94)	0.89 (0.62-0.97)	0.64 (0.32-0.87)	0.75 (0.47-0.91)
Impulse 0-250 ms	0.81 (0.39-0.95)	0.91 (0.69-0.97)	0.88 (0.56-0.96)	0.87 (0.54-0.96)
Impulse 0-300 ms	0.89 (0.63-0.97)	0.89 (0.65-0.97)	0.79 (0.28-0.94)	0.87 (0.52-0.96)

(RFD) Rate of force development; (Vel) Velocity.

Table 3.7. Intraclass correlations (ICC) and 95% confidence intervals (95% CI) for isokinetic muscle test

Test	ICC (95% CI)							
	Concentric				Eccentric			
	Right		Left		Right		Left	
	Within-day	Between-days	Within-day	Between-days	Within-day	Between-days	Within-day	Between-days
Quadriceps Muscle								
Peak Torque	0.99 (0.99-0.99)	0.99 (0.95-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.97-0.99)	0.99 (0.99-0.99)
Peak Torque to Body weight	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.98-0.99)	0.99 (0.97-0.99)	0.99 (0.98-0.99)	0.99 (0.99-0.99)	0.99 (0.94-0.99)	0.98 (0.91-0.99)
Work to Body Weight	0.99 (0.96-0.99)	0.99 (0.95-0.99)	0.94 (0.77-0.98)	0.93 (0.72-0.98)	0.99 (0.99-0.99)	0.99 (0.97-0.99)	0.99 (0.96-0.99)	0.99 (0.96-0.99)
Hamstring Muscle								
Peak Torque	0.98 (0.92-0.99)	0.98 (0.95-0.99)	0.98 (0.95-0.99)	0.98 (0.95-0.99)	0.99 (0.98-0.99)	0.99 (0.98-0.99)	0.99 (0.97-0.99)	0.98 (0.94-0.99)
Peak Torque to Body weight	0.99 (0.96-0.99)	0.99 (0.96-0.99)	0.97 (0.89-0.99)	0.97 (0.88-0.99)	0.99 (0.98-0.99)	0.99 (0.97-0.99)	0.99 (0.97-0.99)	0.99 (0.98-0.99)
Work to Body Weight	0.98 (0.94-0.99)	0.99 (0.95-0.99)	0.98 (0.92-0.99)	0.98 (0.92-0.99)	0.97 (0.90-0.99)	0.97 (0.88-0.99)	0.97 (0.89-0.99)	0.98 (0.92-0.99)
Ankle Plantar Flexors Muscle								
Peak Torque	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.98-0.99)	0.99 (0.97-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.97-0.99)	0.99 (0.98-0.99)
Peak Torque to Body weight	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.98-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)
Work to Body Weight	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.97-0.99)	0.99 (0.99-0.99)	0.99 (0.98-0.99)	0.99 (0.98-0.99)	0.98 (0.93-0.99)	0.99 (0.95-0.99)
Hip Extensors Muscle								
Peak Torque	0.99 (0.98-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.98-0.99)
Peak Torque to Body weight	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.95-0.99)	0.99 (0.99-0.99)
Work to Body Weight	0.99 (0.98-0.99)	0.99 (0.98-0.99)	0.99 (0.98-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)	0.99 (0.97-0.99)	0.99 (0.99-0.99)	0.99 (0.99-0.99)

Table 3.8. Mean and standard error of measurements (%SEM) for hop tests, 2-D FPPA tests, balance tests, and force tests

Test	Mean (%SEM)			
	Within-day		Between-days	
	Right Leg	Left Leg	Right Leg	Left Leg
Hop Tests				
Single Hop (%leg length)	113.38 (7.7%)	116.82 (4.9%)	115.08 (5.7%)	113.39 (6.7%)
Crossover Hop (%leg length)	320.59 (2.3%)	317.35 (2.2%)	323.66 (2.3%)	321.82 (2.2%)
2-D FPPA Tests				
Hop Land (FPPA ˚)	8.44 (9.6%)	8.07 (11.8%)	7.59 (9.5%)	7.65 (10.7%)
Squat (FPPA ˚)	7.81 (9.1%)	8.62 (9.7%)	8.43 (7.7%)	8.03 (8%)
Balance Tests				
Straight Leg (cm^2)	1.36 (4.4%)	1.53 (2.6%)	1.38 (3.6%)	1.54 (2.6%)
Bent Leg (cm^2)	1.39 (2.2%)	1.53 (2.6%)	1.39 (2.2%)	1.52 (2.6%)
Hop Land (sec)	0.398 (2.5%)	0.402 (2.5%)	0.395 (2.5%)	0.404 (2.5%)
Force Tests				
Squat Hop				
Maximum RFD (N·sec/kg)	57.03 (2.8%)	61.89 (2.7%)	57.48 (3.9%)	61.3 (3.5%)
Peak Force (N/kg)	17.06 (1.9%)	18.17 (2%)	17.21 (2.7%)	18.32 (2.1%)
Peak Power (W/kg)	20.94 (1.5%)	22.19 (2.8%)	21.01 (1.5%)	22.31 (2.7%)
Peak Vel ($m\cdot s^{-1}$)	1.48 (3.4%)	1.55 (3.2%)	1.49 (3.4%)	1.55 (1.9%)
Countermovement Hop				
Maximum RFD (N·sec/kg)	81.57 (2.6%)	71.74 (3.2%)	81.86 (2.6%)	70.50 (3.4%)
Peak Force (N/kg)	18.77 (1.5%)	18.46 (2.6%)	18.91 (1.6%)	18.58 (3.2%)
Peak Power (W/kg)	23.70 (2%)	23.75 (2.4%)	23.85 (2%)	23.78 (2.4%)
Peak Vel ($m\cdot s^{-1}$)	1.60 (1.3%)	1.66 (1.8%)	1.61 (1.2%)	1.65 (1.2%)
Ten Consecutive Hops				
Maximum RFD (N·sec/kg)	83.29 (3%)	83.68 (2.6%)	84.39 (3%)	84.85 (2.6%)
Peak Force (N/kg)	16.54 (2.5%)	16.57 (2.4%)	16.68 (2.6%)	16.66 (2.4%)
Peak Power (W/kg)	18.70 (2.2%)	18.90 (2.4%)	19.00 (2.2%)	19.18 (2.4%)
Peak Vel ($m\cdot s^{-1}$)	1.35 (1.5%)	1.19 (1.7%)	1.37 (1.5%)	1.22 (1.6%)
IMTP				
Maximum RFD (N·sec/kg)	36.62 (2.9%)	35.63 (5.2%)	36.86 (2.9%)	35.85 (4.4%)
Peak Force (N/kg)	17.82 (1.9%)	17.90 (2%)	17.76 (1.9%)	18.03 (1.9%)
Impulse 0-100 (Ns/kg)	0.997 (2%)	0.995 (2%)	0.995 (2%)	1.0 (2%)
Impulse 0-200 (Ns/kg)	1.97 (1%)	1.98 (1%)	1.96 (1.5%)	1.99 (1%)
Impulse 0-250 (Ns/kg)	2.47 (0.81%)	2.47 (0.81%)	2.47 (0.81%)	2.48 (0.81%)
Impulse 0-300 (Ns/kg)	2.98 (1%)	2.97 (0.67%)	2.97 (1%)	2.97 (0.67%)

(RFD) Rate of force development; (Vel) Velocity.

Table 3.9. Mean and standard error of measurements (%SEM) for isokinetic muscle test

Test	Mean (%SEM)							
	Concentric				Eccentric			
	Right		Left		Right		Left	
	Within-day	Between-days	Within-day	Between-days	Within-day	Between-days	Within-day	Between-days
Quadriceps Muscle								
Peak Torque (N·m)	183.34 (3.6%)	184.34 (3.5%)	182.6 (3.8%)	184.57 (3.7%)	216.54 (3.6%)	218.7 (3.5%)	215.3 (3.2%)	215.15 (3.2%)
Peak Torque to Body weight (%)	213.36 (3.7%)	214.66 (3.8%)	218.83 (3.8%)	221.66 (3.8%)	257.48 (3.4%)	259.18 (3.6%)	260.66 (3.2%)	262.48 (4.6%)
Work to Body Weight (%)	111.62 (2.6%)	112.92 (2.6%)	114.92 (6.8%)	115.91 (7.8%)	151.45 (3.1%)	149.81 (3.2%)	152.57 (3.2%)	154.02 (3.2%)
Hamstring Muscle								
Peak Torque (N·m)	129.17 (2.1%)	129.7 (2.1%)	131.33 (2.5%)	131.65 (2.5%)	132.95 (1.6%)	134.03 (1.6%)	135.96 (1.8%)	137.11 (2.5%)
Peak Torque to Body weight (%)	151.97 (2%)	153.69 (2%)	152.88 (2.9%)	155.47 (3%)	157.65 (1.7%)	159.35 (1.7%)	159.56 (2%)	160.45 (2%)
Work to Body Weight (%)	95.47 (3.9%)	97.83 (2.8%)	104.44 (4.1%)	107.2 (4%)	114.87 (3.6%)	116.81 (3.4%)	115.87 (3.3%)	117.76 (2.7%)
Ankle Plantar Flexors Muscle								
Peak Torque (N·m)	154.91 (3.3%)	156.06 (3.3%)	148.38 (3.2%)	149.92 (3.2%)	183.35 (2.9%)	183.58 (2.8%)	178.35 (2.7%)	180.91 (2.7%)
Peak Torque to Body weight (%)	183.38 (3.4%)	184.75 (3.2%)	174.85 (3.3%)	177.4 (3.3%)	211.33 (3.1%)	212.7 (3.1%)	207.46 (3%)	208.85 (3%)
Work to Body Weight (%)	62.21 (5.1%)	62.95 (4.9%)	58.72 (4.7%)	59.26 (4.9%)	88.78 (3.8%)	89.89 (3.7%)	85.17 (5.6%)	85 (3.9%)
Hip Extensors Muscle								
Peak Torque (N·m)	193.77 (3.1%)	193.88 (3.1%)	185.62 (3.1%)	187.31 (3.1%)	208.7 (2.7%)	210.48 (2.6%)	201.68 (2.8%)	202.26 (2.8%)
Peak Torque to Body weight (%)	221.06 (3.1%)	221.31 (3%)	213.63 (3%)	215.72 (3%)	243.84 (2.7%)	246.43 (2.7%)	232.21 (2.9%)	235.56 (2.9%)
Work to Body Weight (%)	98.81 (3%)	99.67 (3%)	95.88 (3.2%)	96.86 (3.2%)	173.05 (3.1%)	175.1 (3%)	167 (3.1%)	169.61 (3%)

Tables 3.10 and 3.11 below show the results of multiple one-way ANOVAs for the assessment of all sessions (one, two, and three) for all tests. Results of multiple one-way ANOVAs for hop tests indicate that there were differences between sessions for both limbs throughout both hop tests. The same results (differences between limbs) were also found in 2-D FPPA tests throughout both tests apart from left leg results during horizontal hop land test show that there were no differences between sessions. Balances tests results indicate that there were no differences between sessions across all the tests for both limbs. For force tests, the same results (no differences between sessions) were found in squat hop, countermovement hop, and IMTP tests apart from left leg results during maximum RFD in countermovement hop test indicate that there were differences between sessions. In ten consecutive hops test, both limbs peak force values and right leg peak velocity values show that there were no

differences between sessions while the rest variables show that there were differences between them. For isokinetic muscle tests, quadriceps muscle strength indicates that there were no differences between sessions for both limbs across all variables apart from left leg concentric work to body weight values show that they were different. Hamstring muscle strength indicate that there were no differences between sessions for both limbs across all variables. The same results, no differences between sessions for both limbs across all variables, were also found in ankle plantar flexors muscle apart from two variables which were left leg eccentric peak torque and left leg concentric peak torque to body weight values show that they were different. There were also no differences found between sessions for both limbs across all variables during hip extensors muscle strength test apart from three variables which were right and left legs eccentric peak torque to body weight values and left leg eccentric work to body weight values show that they were different.

Table 3.10. Results of multiple one-way ANOVAs for the assessment of all sessions (one, two, and three) for hop tests, 2-D FPPA tests, balance tests, and force tests

Test	Right Leg	Left Leg
	p Value	*p* Value
Hop Tests		
Single Hop	0.013*	0.007*
Crossover Hop	0.028*	0.002*
2-D FPPA Tests		
Hop Land	0.004*	0.288
Squatting	0.039*	0.044*
Balance Tests		
Straight Leg	0.302	0.786
Bent Leg	0.988	0.259
Hop Land	0.470	0.399
Force Tests		
Squat Hop		
Maximum RFD	0.507	0.275
Peak Force	0.254	0.363
Peak Power	0.447	0.137
Peak Vel	0.790	0.967
Countermovement Hop		
Maximum RFD	0.538	0.018*
Peak Force	0.324	0.329
Peak Power	0.054	0.331
Peak Vel	0.158	0.590
Ten Consecutive Hops		
Maximum RFD	0.015*	0.001*
Peak Force	0.129	0.573
Peak Power	0.001*	0.006*
Peak Vel	0.238	0.001*

IMTP		
Maximum RFD	0.068	0.373
Peak Force	0.671	0.283
Impulse 0-100 ms	0.916	0.495
Impulse 0-200 ms	0.274	0.328
Impulse 0-250 ms	0.495	0.470
Impulse 0-300 ms	0.428	0.438

(RFD) Rate of force development; (Vel) Velocity; (*) Statistically significant

Table 3.11. Results of multiple one-way ANOVAs for the assessment of all sessions (one, two, and three) for isokinetic muscle test

Test	Right Leg Con.	Left Leg Con.	Right Leg Ecc.	Left Leg Ecc.
	p Value	*p* Value	*p* Value	*p* Value
Quadriceps Muscle				
Peak Torque	0.108	0.189	0.087	0.591
Peak Torque to Body weight	0.311	0.251	0.486	0.057
Work to Body Weight	0.465	0.034*	0.295	0.140
Hamstring Muscle				
Peak Torque	0.122	0.517	0.149	0.285
Peak Torque to Body weight	0.235	0.122	0.111	0.609
Work to Body Weight	0.058	0.084	0.247	0.224
Ankle Plantar Flexors Muscle				
Peak Torque	0.404	0.361	0.978	0.043*
Peak Torque to Body weight	0.229	0.021*	0.291	0.328
Work to Body Weight	0.330	0.325	0.405	0.410
Hip Extensors Muscle				
Peak Torque	0.994	0.366	0.165	0.878
Peak Torque to Body weight	0.583	0.073	0.040*	0.005*
Work to Body Weight	0.201	0.357	0.241	0.002*

(Con) Concentric; (Ecc) Eccentric; (*) Statistically significant

3.6 Discussion

The purposes of this chapter were to:

1. Examine the within- and between-days reliability of five tests, which are hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic muscle tests.
2. Establish standard measurement error (%SEM) during these tasks in recreationally healthy participants.

In the present investigation, the within-day ICC range value for hop tests was slightly lower than for the between-days results and the reason behind this might be seen as a result of fatigue as repeating all the tests in the same day (after one hour of rest). This ICC in this study is similar to the results in Bolgla and Keskula's (1997) study which investigated the test re-test reliability of the single-leg hop for distance and crossover hop test in 20 participants (5 males and 15 females). Their ICC was 0.96 for single hop, and 0.96 for crossover hop for distance. In the same study, a repeated scores analysis of variance revealed no difference between each trial score except for the single-leg hop for distance. Therefore, the authors have concluded that this difference represents a learning effect not reported in the other tests. However, the test-retest intervals used in their study do not replicate a clinical setting (48 hours), as test-retest sessions are usually separated by 4-6 weeks (Worrell et al., 1993; DeCarlo et al., 1999; Unger and Wooden, 2000). The time that separates test-retest sessions may affect reliability (Currier, 1990; Ross, 1997), therefore, it was necessary to evaluate the single-leg horizontal hop and crossover hop tests' reliability using time intervals between testing sessions that more closely replicate the timeframes that may be used in a clinical setting (Ross, 1997). Additionally, the same study does not provide information about subjects' activity levels; this is an essential point because the results from an athletic group will not be useful to assess sedentary people and vice versa. Furthermore, their study used an unequal number of men and women and the authors have stated that learning affects were present, which may have invalidated the reliability values of the study. Although this study has adequately investigated differences between trials, the study reports that three practice trials were sufficient for the crossover hop test only, while four trials may be required for the single hop test. The study concludes that further examination of learning affects associated with the hop tests is needed. Moreover, they did not normalise the hop distance to body weight and this is also an essential point to provide an accurate ICC and SEM range results. Another study carried out by Ross et al. (2002) investigated the reliability of hop tests with a time interval of about four weeks between two testing sessions. The study indicates excellent reliability (ICC's 0.92-0.97) for the four single-leg hop tests, which is also close to the findings in the current study.

The ICC range value of the 2-D FPPA test for within-day was also slightly lower than the between-days values, and this is slightly further than the results found by Munro et al. (2012) during SLS, drop jump and single-leg landings from a standard 28-cm step. They found fair to good ICC results ranging between 0.59 and 0.88 for within-day, while for between-days ICCs showed good to excellent results ranging from 0.72 to 0.91, and their SEM data ranged from 2.72° to 3.01°. Therefore, future work on the reliability of 2-D FPPA is required. However, it is unclear whether increasing knee flexion angles would affect the amount of FPPA measured. In addition, placing the markers in the current study during 2-D FPPA test after seven days for re-testing seems to be better than placing them during the within-day test. One of the factors that might affect reliability of the 2-D especially during single-leg horizontal hop for distance test was that there may have been some underestimate or overestimate of FPPA when a true perpendicular angle was not calculated. However, trials that were not in align were removed and repeated and this could have made some slight error.

For the balance tests, the sway area and TTS, the ICC range value for the within-day tests was exactly the same as the between-days results. This results are almost confirmed by Birmingham (2000) who found fair to excellent reliability values for COP, with ICC ranging between 0.41 and 0.91. The author in the previous study measured the total length of the COP path throughout three repetitions, under four different testing conditions. Similarly, four testing conditions have been used in another study by Bauer et al. (2008), who explain the influence of the visual dimension on the reliability of examining COP and reported better reliability in tasks with closed eyes than open. However, all COP variables (mean area, length, medial/lateral and anterior/posterior sway) found good to excellent reliability values ranging between (0.84 - 0.95). Nevertheless, in the study by Bauer et al. (2008), data was collected from 63 participants, all of them above the age of 62 years (mean age = 78.74 years), and this is totally different group to the subjects which have been involved in the current study. Another limitation of the previous study is the limited number of trials, as implementing only three trials makes it difficult to decide whether the missing learning effect was the actual cause of the difference found between the tests with eyes open and eyes closed. As explained previously in the literature review, more trials would be beneficial to ensure the reliability of the parameters. For TTS measurement reliability, it has been reported by Ross et al. (2005), with the ICC values of 0.79 for anterior/posterior and 0.65 for medial/lateral TTS. The subjects in this study were required to maintain a single-leg position for 20 seconds, and this study concluded that TTS represents a reliable parameter for evaluating postural control. However, in their study, they allowed the participants to use different landing techniques, and this is a potential limitation to these single-leg hop findings. Single-leg hop TTS differences, for example, can basically be a result of groups using various strategies to land and stabilise when doing a jump landing.

The ICC range values of force tests were almost similar in both within-day and between-days results. For squat hop the ICC range value for the within- and between-days results for all variables was excellent. This has been confirmed by Moir et al. (2005) who investigated the bilateral SJ reliability in nine physically active men using a force platform. Their ICC results for peak force (PF) was 0.96 bilaterally and for the current study ranged from 0.93 to 0.99 for both right and left legs individually; their peak RFD was 0.53 bilaterally and for this study was 0.99 for both right and left legs individually; their takeoff velocity was 0.93 bilaterally and for this study ranged from 0.92 to 0.97 for both right and left legs individually, and their peak power was 0.97 bilaterally and this one was 0.99 for both legs individually. However, they did not normalise their data to body weight, which might have invalidated the final results, as the data might not match with the characteristics and differences in weight for the recruited subjects.

For countermovement hop, the ICC range value for the within- and between-days results for all variables was also excellent. This is confirmed by Sheppard et al. (2008), who investigated the bilateral CMJ reliability in a total of 26 subjects. The measurements of PF, peak RFD, peak velocity, peak power, and relative power (normalised to body weight) were reported for each jump. The ICC for PF was excellent (0.96), peak RFD was fair (0.43), peak velocity was poor (0.25), peak power was good (0.80), and relative power was fair (0.74), which indicates that the force characteristics of CMJ are reliable when using this test's methodology. While in the current study, countermovement hop for PF ranged from 0.98 to 0.99 for both legs individually, peak RFD was 0.99 for both legs individually, peak velocity was 0.99 for both legs individually, and peak power was also 0.99 for both legs individually. However, the differences between these results and their results may be because they did their study bilaterally and this one was implemented unilaterally. In addition, all the data in the current study has been normalised to body mass, whereas they only normalised one variable which is power, and this may make their results more variable.

For 10 consecutive hops, the ICC range value for the within- and between-days results for all variables was also excellent. However, the within and between-days reliability for the 10 consecutive hops tests has not been done before, making comparison almost impossible because of the lack of any previous studies. Therefore, further investigations are needed in this area to confirm the findings.

For IMTP, the ICC range value for the within- and between-days results for the peak RFD and PF variables was also excellent, and for the impulses 0-100, 200, 250, and 300 ms was ranged from fair to excellent. Peak force and peak RFD have been confirmed by Kawamori et al. (2006), as the results of their study show excellent values for both PF and peak RFD with ICC of 0.97 and 0.96, respectively. However, it was carried out bilaterally which is different to the method used in this study (unilaterally). Another within-day reliability study was carried out by Comfort et al. (2015), and the PF value was 0.99, maximum RFD was 0.90, impulse 100 ms was 0.95, impulse 200 ms was 0.96, impulse 300 ms 0.95. The within-day PF data for the current study was 0.99 for both legs individually, and the maximum RFD ranged from 0.96 - 0.99. However, the impulses range for 0-100 ms ranged from 0.54 - 0.55, 0-200

ms ranged from 0.80 - 0.89, for 0-250 ms ranged from 0.81 - 0.91, and for 0-300 ms it was 0.89 unilaterally. The reason for the slightly low ICC range for impulses is because it seemed like the participants were confused about pulling the bar- sometimes they used explosive movements in pulling and sometimes they pulled gently, which made these results vary.
Finally, the ICC range value of all isokinetic muscle test variables (concentric and eccentric) for all muscles was also excellent for both the within- and between-days results. These results have been confirmed by Feiring et al., (1990) who reported the ICC of the quadriceps strength values ranged from 0.95 to 0.97 for peak torque, and from 0.95 to 0.97 for total work; while their ICC for hamstring values ranged from 0.82 to 0.99 for peak torque, and from 0.93 to 0.96 for total work. Similarly, for Lund et al., (2005) in their reliability study, they found good to excellent reliability with respect to knee flexion and extension, as ICC ranged between 0.89 and 0.98. Moreover, Tsiros et al., (2011) carried out a reliability study with children, and they found that the peak isokinetic knee extension and flexion torque had ICCs of 0.96. Another reliability study by Maffiuletti et al. (2007) found from 0.98 to 0.99 for the peak torque of knee actions concentrically and eccentrically. For ankle plantar flexor ICC measures, Webber and Porter (2010) investigated the reliability of isokinetic ankle measures in older women, and their ICCs for the PF tests ranged between 0.58 and 0.93. Finally, in the study by Claiborne et al. (2009), their aim was to find out the test-retest reliability of isokinetic hip torque using a Biodex Isokinetic Dynamometer at a speed of 60˚/sec. for both right and left hip flexion/extension. They demonstrated good reliability for the torque results which were (0.76 - 0.90) concentrically and eccentrically. Nonetheless, it was difficult to compare the results from this study for the peak torque to body weight for all of the lower limb muscles as this has not been examined previously, except in one study by Pincivero et al. (1997), which demonstrated the reliability of peak torque to body weight of knee extension and flexion during concentric muscle action, ranging from 0.76 to 0.92.

The majority of the results of multiple one-way ANOVAs for all tests indicate that there were no differences between sessions for both limbs apart from some tests and variables (as explained above in the results section) show that they were different, and the possible reason for having such differences might be occurred as a result of learning effect. It is important to note several limitations in the current study. Firstly, no power calculation has been applied, and the choice of the sample size is simply in comparison to previous studies. The second limitation is that the accuracy and magnitude of 3-D lower limb joint rotations during any activity cannot be fully replicated by 2-D FPPA measurements. However, in the absence of 3-D measurements, 2-D still can provide a reliable and valid measure of gross lower limb kinematics (Munro et al., 2012). Another limitation of this study is that it is still unclear whether decreased knee-flexion angles (during initial contact) can affect the amount of dynamic knee valgus measured, as only FPPA at the maximum knee-flexion angle were measured, therefore further investigation into this as a possible contributing factor is needed. Furthermore, the population included in the current study are all healthy, recreationally active university students. However, it is still unclear whether all the tests may have been influenced by age or by level of sporting activity, therefore these findings may not be valid for younger or older age groups, or highly athletic or injured populations, which also require further studies with other populations. It also has to be acknowledged that only the intrarater reliability of all tests has been measured, and therefore, further investigation looking at interrater reliability is required.

3.7 Conclusion

Based on the results of the study, all the hypotheses have been accepted and the following results can be highlighted:

- The majority of the ICC values for all tests, which are hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic muscle tests, are excellent across all variables during within- and between-day sessions, showing these tests to be reliable.
- Impulses from 0 - 100, 200, 250, 300 ms had less reliable variables across all IMTP results.

Chapter (4)

Symmetry of Performance Across Tests Between Right and Left Legs

4 Chapter 4: Symmetry of Performance Across Tests Between Right and Left Legs

4.1 Aims

1. Investigate the differences between right and left leg performances across all tests: hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic muscle tests.

2. Describe reference values for LSI for hop tests and isokinetic muscle strength tests for recreationally healthy participants.

4.2 Background

Most rehabilitation programs use some form of testing to determine readiness to return to sport, or to determine the functional limitations of the lower limbs; however, it is important to determine what the pass criteria is. One of the most common return to sport criteria reported in the literature is 85% to 90% for the limb symmetry index (LSI). Munro and Herrington (2011) found that the average LSI for the four hop tests (single, triple, crossover, and 6-meters timed hop) was 100 percent (98.38 - 101.61 %.) and that 100 percent of healthy participants have at least an LSI of 90%. Therefore, and based on Munro and Herrington's (2011) results, the it is advocated that the return to sport LSI criteria for hop tests should be increased to 90% from the previous recommended 85% (Noyes et al., 1991).

In order to assess the functional limitations of the lower extremities, physical examinations under simulated activity conditions are required (Barber et al., 1990). Several studies using different testing protocols have been designed to objectively measure these limitations. One study has demonstrated the effectiveness of five different function tests related to hop performance for detecting lower extremity functional deficiencies (Barber et al., 1990). A limb symmetry index of 85% or greater was found during different hop tests to be within the normal range for both genders, regardless of dominance or sports activity level (Noyes et al., 1989). Noyes et al. (1991), report that the results from their previous studies underscore the need to improve tests so that they are better able to define functional limitations.

Many studies have already evaluated asymmetry between limbs in performance during various single leg hops, which have been undertaken from a standing position (Hewit et al., 2012; Swearingen et al., 2011; Meylan et al., 2010; Miyaguchi and Demura, 2010; de Ruiter et al., 2010; Schiltz et al., 2009; Maulder and Cronin, 2005). Some studies have reported that the performance of a single leg vertical hop from standing position was significantly higher in the dominant leg than in the non-dominant leg (Swearingen et al., 2011; Meylan et al., 2010; Miyaguchi and Demura, 2010). Moreover, Meylan et al. (2010) evaluated a similar phenomenon in the horizontal and lateral countermovement jumps. Schiltz et al. (2009) also reported that professional basketball players jumped dramatically higher with the dominant leg than the non-dominant leg (12%) in a drop jump.

Regarding muscle strength symmetry, it is usually considered to be substantial asymmetry if the difference between limbs is greater than 15 % in healthy athletes, and this may put the limbs at increased risk of injury (Knapik et al., 1991). Willigenburg et al. (2014) state that asymmetries between limbs in strength and function could affect athletic performance. They found that LSI for quadriceps peak torque was (98.9 %) and peak torque to body weight was (99.3 %), while for hamstrings peak torque it was (94.2 %), and peak torque to body weight was (94.6 %) at a speed of 60°/s between the dominant and non-dominant limbs in 22 healthy participants.

Regarding force tests symmetry, the purpose of the study implemented by Bell et al. (2014) was to (a) evaluate how asymmetry in lower limb lean mass influenced force and power asymmetry in jumping tasks, (b) investigate how force and power asymmetry affected jump height. A bilateral CMJ was performed on a portable platform with separate force plates for each limb in 167 collegiate athletes. For the PF value, they found that the percentage of individuals falling within a percent asymmetry of 0-5 was 52%, 5-10 was 27%, 10-15 was 16%, and > 15 was 4%. While for the peak power value, they found that the percentage of individuals falling within percent asymmetry of 0-5 was 66%, 5-10 was 29%, 10-15 was 4%, and > 15 was 2%. This indicates that PF and peak power values were almost symmetrical during CMJ activity.

When assessing balance tests symmetry, Holm et al. (2004) carried out a study to investigate the effect of a neuromuscular training program on balance and proprioception in elite handball players. Thirty-five female handball players from two different teams in the elite division participated. The authors found a significant improvement in dynamic balance between the first and second tests. The improvement in dynamic balance was found one year post training. No changes were found for static balance. Furthermore, the results from the proprioception device showed that there were no differences between the right and left legs.

2-D FPPA symmetry has been assessed by Munro et al. (2012). Munro et al. (2012) examined the reliability and differences between the left and right legs using the 2-D analysis of lower limb dynamic knee valgus in 20 recreationally active university students. Subjects applied SLS, drop jump, and single-leg landing tests. The authors used the data from tests one and three to investigate the differences between sex and limbs. They found no differences between the left and right legs in either sex.

Therefore, the aim of this study is to investigate the differences between right and left leg performances across all tests, which are hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic muscle tests. In addition, the reference values for LSI for hop tests and isokinetic muscle strength tests in recreational healthy participants will be described.

4.3 Study Hypotheses (H)

Five hypotheses have been formulated based on the review of the literature:

H1. There is no difference between measurement scores examined for both legs for two hop tests, which are horizontal single-leg hop for distance and crossover hop tests.

H2. There is no difference between measurement scores examined for both knees for 2-D FPPA tests during squat and horizontal single-leg hop land tests.

H3. There is no difference between measurement scores examined for both legs for both static and dynamic balance tests.

H4. There is no difference between measurement scores examined for both legs for force generation tests for different vertical hop tests and IMTP test.

H5. There is no difference between measurement scores examined for both legs for isokinetic muscle testing, which are hip extensors, quadriceps, hamstring, and ankle plantar flexor muscles for both concentric and eccentric muscle actions.

4.4 Methods

4.4.1 Participants

20 Recreationally active healthy students, undergraduate and postgraduate, from Applied Sports Science and Physiotherapy programmes as well as Sport Rehabilitation courses, were recruited to take part in the study: 11 males and nine females, (age 33.65±3.47 years; height 170.9±5.87 cm; and body mass 81.05±15.93 kg). Subjects were physically active and had performed at least 30 minutes of physical activity three times a week on a regular basis over the last six months (Munro and Herrington, 2011). Table 4.1 below presents the descriptive statistics for the characteristics of these participants. Mean and standard deviation for the age, height and weight of the participants are also summarised.

Table 4.1. Demographic data for all participants (N=20)

	Range		**Mean**	**Standard Deviation**
	Minimum	Maximum		
Age (Years)	25	41	33.65	3.47
Height (Centimetres)	157	178	170.90	5.87
Weight (Kilograms)	56	116	81.05	15.93

4.4.1.1 Inclusion Criteria

1. Healthy participants able to stand, bend their legs, hop, and land independently.

2. Over 18 years of age.

3. Able to give informed consent.

4.4.1.2 Exclusion Criteria

1. Subjects with pathology or pain in a lower limb affecting standing, bending legs, and hopping or landing ability.

2. Lower-limb injury during the last year.

3. Lower-limb deformities.

4. Unable to give informed consent.

Before participation, each subject read the information sheet and signed the informed consent form which was approved by the Research, Innovation and Academic Engagement Ethical Approval Panel at the University of Salford (Appendix A).

4.4.2 Facilities and Resources

The experimental procedures were conducted in the Human Performance Laboratory at the University of Salford. All equipment required for the research was already available within the Directorate of Sport, therefore, no funding was needed for the testing. The study analysis and results will remain anonymous and confidential and only able to be accessed by the researcher.

4.4.3 Procedure

For each participant, the measurements of the performance of all five different tests were taken for both legs individually. Subjects were asked to wear their own training shoes, with these shoes being the ones they wear the majority of the time for their training activities. Participants took part in one experimental test on one day. Two minutes rest period was given in between each test (Corriveau et al., 2000), with half a minute rest between trials. All subjects were asked not to perform any exercise in the 24 hours prior to testing day and also not to eat one hour before the testing session (Munro and Herrington, 2011).

The tests were:

1. **Hop Tests:**
    - A. Single-leg horizontal hop for distance test.
    - B. Single-leg crossover hop test.
2. **2-D FPPA:**
    - A. SLS.
    - B. Single-leg horizontal hop for distance.
3. **Balance Tests:**
    - A. Straight leg (sway area).
    - B. Bent (30˚) leg (sway area).
    - C. Single-leg horizontal hop land (TTS).
4. **Force Generation Tests:**
    - A. Squat hop.
    - B. Countermovement hop.
    - C. Ten consecutive hops.
    - D. Isometric mid-thigh pull.
5. **Isokinetic Muscle Tests:**
    - A. Quadriceps muscle.
    - B. Hamstring muscle.
    - C. Ankle plantar flexor muscles.
    - D. Hip extensor muscles.

The procedure has previously been described and explained in detail in the methods chapter (Chapter 2).

4.4.4 Statistical Analysis

ALL statistical analyses were performed using SPSS software (v. 21, SPSS Inc., Chicago, IL). Descriptive analysis (mean and standard deviation) for each dependent variable was performed. All data were tested for normality using a Shapiro-Wilk test to check whether data were normally distributed or not (parametric or non-parametric), values were not normally distributed if they were equal to or less than ≤ 0.05 (p-value was set at 0.05). Limb differences were determined using a paired t-test for parametric variables and a Wilcoxon Rank Test for non-parametric variables. The mean value of the three measures (trials) for each test was calculated to find out the differences between the right and left leg's performance during all the tests. Force data was normalised to body weight, and hop data was normalised to leg length, as explained in depth in the data processing and analysis section in the methods chapter (Chapter 2). The LSI for hop tests and isokinetic muscle strength tests was calculated from the following equation: left leg mean values divided by right leg mean values then × 100.

4.5 Results

The normality tests found that all hop tests were normally distributed; FPPA tests were normally distributed; balance tests were normally distributed apart from right bent leg (30˚), and left leg TTS tests were not normally distributed; force test variables were normally distributed apart from left leg PF value in squat hop; left leg maximum RFD and peak power in countermovement hop; left leg maximum RFD and impulses from 0-100, 200, and 250 ms in IMTP were not normally distributed. Isokinetic muscle strength variables were also normally distributed, apart from both legs' concentric and eccentric peak torque values for the quadriceps muscle, and both legs' eccentric work to body weight values for the hamstring muscle. For the Shapiro-Wilk test, the results for all variables were measured during all the tests (see Appendix C).

Table 4.2 below shows descriptive statistics for all collated data, including the mean and standard deviation for each variable. Moreover, it provides a summary of normal values for all the tests in the healthy population. In addition, the same table explains the differences between right and left leg performance. In all the tests there were no differences found between right and left leg performance.

Table 4.2. Data collected for all the tests (N=20), and illustrates the differences between right and left leg performance

Tests				Right Leg		Left Leg				
				Mean	SD	Mean	SD	Absolute Difference	*p* Value	PWR
Hop	Single-leg Hop for Distance (% leg length)			127.20	26.79	124.73	24.44	2.47	0.252	0.39
	Crossover Hop (% leg length)			361.04	83.66	357.57	78.47	3.47	0.107	0.14
2-D	Squat (FPPA °)			7.73	4.07	8.10	4.48	0.37	0.618	0.76
	Hop Land (FPPA °)			8.65	4.99	7.72	3.45	0.93	0.213	0.50
Balance	Straight Leg (cm^2)			1.34	0.33	1.52	0.40	0.18	0.103	0.86
	Bent Leg (cm^2)			1.44	0.40	1.50	0.43	0.06	0.360	0.61
	Hop Land (TTS) (sec)			0.39	0.06	0.40	0.05	0.01	0.852	0.96
Force	Squat Hop	Max RFD (N·sec/kg)		66.22	22.92	71.85	27.13	5.63	0.117	0.45
		Peak Force (N/kg)		18.34	2.57	18.54	3.12	0.2	0.99	0.99
		Peak Power (W/kg)		23.05	4.21	23.19	5.32	0.14	0.887	0.91
		Peak Velocity (m·s^{-1})		1.54	0.20	1.56	0.29	0.02	0.733	0.85
Force	Countermovement Hop	Max RFD (N·sec/kg)		83.06	23.53	77.00	30.89	6.06	0.079	0.38
		Peak Force (N/kg)		19.24	2.62	19.04	3.01	0.2	0.467	0.60
		Peak Power (W/kg)		24.71	4.40	24.49	4.70	0.22	0.737	0.80
		Peak Velocity (m·s^{-1})		1.65	0.19	1.67	0.21	0.02	0.635	0.79
Force	Ten Consecutive Hops	Max RFD (N·sec/kg)		86.83	24.92	89.40	25.02	2.57	0.198	0.34
		Peak Force (N/kg)		16.98	3.65	18.16	4.32	1.18	0.087	0.51
		Peak Power (W/kg)		19.88	3.87	21.15	5.13	1.27	0.131	0.61
		Peak Velocity (m·s^{-1})		1.43	0.22	1.45	0.41	0.02	0.801	0.89
Force	IMTP	Max RFD (N·sec/kg)		41.21	11.48	41.04	12.37	0.17	0.794	0.81
		Peak Force (N/kg)		18.35	3.29	18.42	3.07	0.07	0.835	0.86
		Impulse 0-100 ms (Ns/kg)		1.001	0.018	0.999	0.025	0.002	0.909	0.96
		Impulse 0-200 ms (Ns/kg)		1.983	0.030	1.984	0.046	0.001	0.981	0.99
		Impulse 0-250 ms (Ns/kg)		2.474	0.038	2.476	0.056	0.002	0.930	0.96
		Impulse 0-300 ms (Ns/kg)		2.970	0.056	2.971	0.061	0.001	0.840	0.86
Isokinetic	Quadriceps	Peak TQ (N·m)	Concentric	185.45	76.30	187.24	69.32	1.79	0.765	0.80
			Eccentric	219.31	78.49	218.79	74.85	0.52	0.550	0.56
		Pk TQ/BW (%)	Concentric	226.70	83.49	230.77	81.52	4.07	0.395	0.48
			Eccentric	270.71	94.45	270.97	88.92	0.26	0.955	0.96
		Work/BW (%)	Concentric	131.44	49.05	130.55	46.40	0.89	0.810	0.83
			Eccentric	168.73	52.30	166.21	50.85	2.52	0.444	0.53
Isokinetic	Hamstring	Peak TQ (N·m)	Concentric	133.12	21.80	130.45	23.26	2.67	0.332	0.54
			Eccentric	134.28	27.12	134.64	28.08	0.36	0.893	0.90
		Pk TQ/BW (%)	Concentric	163.33	33.87	162.15	26.94	1.18	0.682	0.73
			Eccentric	166.47	29.24	165.81	32.06	0.66	0.810	0.84
		Work/BW (%)	Concentric	113.06	41.52	116.77	39.14	3.71	0.202	0.33
			Eccentric	123.19	25.42	121.68	22.48	1.51	0.575	0.67
Isokinetic	Ankle Plantar Flexors	Peak TQ (N·m)	Concentric	171.95	51.16	168.46	49.05	3.49	0.229	0.33
			Eccentric	196.86	51.03	196.71	48.78	0.15	0.958	0.96
		Pk TQ/BW (%)	Concentric	213.27	67.42	210.57	67.79	2.7	0.251	0.31
			Eccentric	241.29	71.10	240.86	68.64	0.43	0.893	0.90
		Work/BW (%)	Concentric	79.73	38.98	80.51	40.81	0.78	0.676	0.71
			Eccentric	109.00	42.59	107.87	43.22	1.13	0.485	0.53
Isokinetic	Hip Extensors	Peak TQ (N·m)	Concentric	178.76	66.75	175.21	61.70	3.55	0.251	0.33
			Eccentric	191.67	64.52	188.94	62.63	2.73	0.360	0.43
		Pk TQ/BW (%)	Concentric	212.89	71.395	209.92	65.44	2.97	0.410	0.48
			Eccentric	230.77	71.40	227.21	69.23	3.56	0.321	0.40
		Work/BW (%)	Concentric	106.27	36.77	106.29	36.62	0.02	0.997	0.99
			Eccentric	171.53	53.47	169.44	52.60	2.09	0.507	0.57

(Peak TQ) Peak torque; (Pk TQ/BW) Peak torque to body weight;

(Work/BW) Work to body weight; (SD) Standard deviation; (PWR) = Power

Table 4.3 below shows the percentage of participants achieving LSI values for hop tests and isokinetic muscles tests. It seems that the majority of the participants achieved 85% of LSI for both tests.

Table 4.3. Percentage of participants achieving LSI values for hop tests and isokinetic muscles tests

LSI				≥ 85	≥ 90	≥ 95
Hop	Single-leg Hop for Distance			100	95	60
	Crossover Hop			100	100	100
Isokinetic	Quadriceps	Peak TQ	Concentric	90	90	60
			Eccentric	90	80	70
		Pk TQ/BW	Concentric	100	100	70
			Eccentric	100	95	80
		Work/BW	Concentric	85	70	60
			Eccentric	95	85	50
Isokinetic	Hamstring	Peak TQ	Concentric	100	80	60
			Eccentric	100	80	75
		Pk TQ/BW	Concentric	100	95	80
			Eccentric	100	90	75
		Work/BW	Concentric	100	95	65
			Eccentric	95	85	65
Isokinetic	Ankle Plantar Flexor	Peak TQ	Concentric	90	90	65
			Eccentric	100	100	75
		Pk TQ/BW	Concentric	95	95	80
			Eccentric	100	100	75
		Work/BW	Concentric	95	95	70
			Eccentric	95	90	65
Isokinetic	Hip Extensors	Peak TQ	Concentric	100	85	55
			Eccentric	100	90	55
		Pk TQ/BW	Concentric	100	85	60
			Eccentric	100	85	60
		Work/BW	Concentric	85	75	60
			Eccentric	95	90	70

(Peak TQ) Peak torque; (Pk TQ/BW) Peak torque to body weight;
(Work/BW) Work to body weight.

4.6 Discussion

The aims of this study were to:

1. Investigate the differences between right and left leg performances across all tests, which are: hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic muscle tests.

2. Describe reference values for the LSI for hop tests and isokinetic muscle strength tests in recreationally healthy participants.

From the results, it can be concluded that there were no differences found between right and left leg performance during all the tests. For hop tests, all participants achieved 85% of LSI for a single-leg hop for distance and crossover hop test, this is confirmed by Noyes et al. (1989) who have reported that a limb symmetry index of 85% or greater was found during different hop tests to be within the normal range for both genders regardless of dominance. Munro and Herrington (2011) found that the average LSI for the four hop tests (single, triple, crossover, and 6-meters timed hop) was 100 percent (98.38 - 101.61 %.) and that 100 percent of healthy participants have at least an LSI of 90%. Therefore, and based on Munro and Herrington's (2011) results, the it is advocated that the return to sport LSI criteria for hop tests should be increased to 90% from the previous recommended 85% (Noyes et al., 1991). Although the findings in the current study (85% of LSI was achieved) are matched with Noyes et al. (1989) findings (which are a slightly lower than Munro and Herrington's (2011) recommendations), this is likely due to the differences in training status.

For 2-D FPPA tests, there were no differences found between the right and left knee angles during squat and single-leg hop for distance tests. The findings are similar to Munro et al. (2012) who examined the differences between the left and right legs using 2-D analysis of the lower limb dynamic valgus in 20 recreationally active university students. Subjects undertook SLS, drop jump, and single-leg landing tests. The authors used the data from tests one and three to investigate the differences between sex and limbs. They found no differences between left and right legs in either sex. Although Munro et al. (2012) used participants who were attending similar physical activity sessions (three times a week) which is similar to what has been participated in the current study, they were younger (average of 22 years) than the current participants (average of 33 years) which indicate that lower limb alignment differences might not influence by age. Also, Munro et al. (2012) used SLS, drop jump, and single-leg land tasks, however, drop jump and single-leg land tests are different than the test which has been used in the current study (single-leg horizontal hop for distance). Maximum single-leg horizontal hop for distance test might be a slightly challenge test as the participants require to maintain their balance after landing.

For balance tests, there were no differences found between the right and left leg for overall balance during both static (sway area) and dynamic (TTS) tests. Another study used a different methodology to assess balance (Holm et al., 2004), and they found that there were no changes for static balance. Moreover, the results from their proprioception device showed that there were no differences between the right and left legs. Nonetheless, Holm et al., 2004 used highly athletes female handball players and this is an important point because results from an athletic group cannot be generalisable to sedentary people and vice versa. Additionally, the authors tested balance using the KAT 2000 which is a slightly different and older tool in measuring balance than force plates. Although all the players in their study had already experience with the KAT 2000 previously and were familiar with the device, they were not given any practice trials prior to the testing and this may invalid the final results because of the learning effect.

For force tests, there were no differences found between the right and left leg performance during the squat hop, countermovement hop, 10 consecutive hops, and IMTP for all variables. Some of the variables have been evaluated previously and confirmed by Bell et al. (2014) during CMJ. A bilateral CMJ was performed on a portable platform with separate force plates for each limb in 167 collegiate athletes. For the PF value, they found that the percentage of individuals falling within a percent of asymmetry of 0-5 was 52%, 5-10 was 27%, 10-15 was 16%, and > 15 was 4%. While for the peak power value, they found that the percentage of individuals falling within a percent of asymmetry of 0-5 was 66%, 5-10 was 29%, 10-15 was 4%, and > 15 was 2%. This indicates that PF and peak power values were symmetrical during CMJ activity. However, in their study they used a bilateral CMJ, which is totally different method to a unilateral countermovement hop, as the subjects with a bilateral CMJ feel more comfortable and controlled when performing the task than a unilateral. Although the authors recruited highly athlete participants in their study and this is different activity level to what has been included in the current study, this indicate that variation in the activity level might not influence lower limb differences with regard force-time characteristics during CMJ.

Regarding muscle strength symmetry, there were no differences found between right and left leg strength for quadriceps, hamstrings, ankle plantar flexors, and hip extensors during the concentric and eccentric muscle actions, including all variables. Furthermore, the majority of the subjects (85% and more) during all muscle strength tests achieved 85% of the LSI for most of the variables, and it is usually considered a substantial asymmetry if the difference between limbs is greater than 15 % in healthy athletes and this may put the limbs at increased risk of injury (Knapik et al., 1991). Willigenburg et al. (2014), state that asymmetries between limbs concerning strength and function could affect athletic performance. They found that LSI for quadriceps peak torque was (98.93) and peak torque to body weight was (99.28), while for hamstrings peak torque it was (94.19) and peak torque to body weight (94.63) at a speed of 60°/s between the dominant and non-dominant limbs in 22 healthy participants. However, it is quite difficult to determine the dominant and non-dominant limb, as some people may define the dominant leg as the leg used when kicking a ball, and others may define the dominant leg as the one planted when kicking a ball. It may also be possible to identify dominance based on either fore production, or performance in a more functional task, e.g. hop distance, however no specific criteria has yet been determined for such procedures. This also provides an additional dilemma if an individual demonstrates strength dominance on one leg but performance in a functional task highlights dominance in the other leg. It is suggested that further investigation be carried out in this area.

4.7 Conclusion

Based on the results of the study, all the hypotheses have been accepted and the following results can be highlighted:

- No differences were found between the right and left leg performances during all the tests.
- Symmetry between limbs exists for both hop tests (100% of participants with ≥ 85% LSI), while symmetry between limbs almost exists for muscle strength tests, from which it can be concluded that one leg's hop performance can define the other.

Chapter (5)

The Relationship Between all the Tests and Hopping Performance in a Healthy Population

5 Chapter 5: The Relationship Between all the Tests and Hopping Performance in a Healthy Population

5.1 Aims

1. To investigate the relationship between all of the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks in a healthy population.

2. Provide the reference values that are needed for each of the individual tests.

5.2 Background

A hop is a common task performed in many sports. During landing from a triple hop, the impact forces produced can reach a magnitude of up to twelve times the body weight (Perttunen et al., 2000) and may result in injury to the lower extremities (Jacobs et al., 2007). Landing involves strong forces being applied by the knee and hip extensors and ankle plantar-flexors to control joint flexion and decelerate the body (Mcnitt-Gray, 1993). When landing, the lower extremities help to absorb and dissipate the ground reaction forces resulting from each hop. If these forces are very great and the body cannot accommodate and control them, there is a risk of injury. In studies on landing, there has been concentration on the biomechanical implications of impact and of the total load on lower limb tissues (Devita and Skelly, 1992). However, during different activities, the landing phase may be overlooked, which might contribute to poor performance or injury. Thus, there has been an increased focus on the factors that contribute to different hop and landing techniques (Dufek and Bates, 1991).

Some injuries such as ACL ruptures have been theorised as being attributable to frequent landing from a hop which requires the subject to maintain their balance (Griffin et al., 2000). Balance can be defined as the ability to keep the centre of gravity of the body within the limits of the base of support (Cook and Woollacott, 2001). Balance testing is an important component in sports outcome measurements, but especially in the sports rehabilitation process, particularly where landing or maintaining balance is a key component of the activity. TTS is a parameter that is used to measure dynamic stability when a subject moves from a dynamic phase into a static phase. Measurement of this outcome has been used under dynamic conditions to examine and compare ACL-deficient and healthy subjects (Phillips and van Deursen, 2008).

Knee injuries may result in reduced quadriceps and hamstring strength (Hiemstra et al., 2000), and ankle injuries if there is increased time to stabilisation (Ross et al., 2005). Higher levels of lower limb strength will potentially result in improved performance (Myer et al., 2006), more controlled landings and a reduction in injuries (Jacobs et al., 2007). Previous studies have noted an association between concentric strength and hop distance (Hamilton et al., 2008). However, eccentric strength is reported to be important in lower limb function and rehabilitation following injury (Lorenz and Reiman, 2011). Moreover, landing requires great eccentric muscle forces to be exerted by the knee, hip and ankle extensor muscles during the control phase, when joints are in a flexed position, in order to decelerate the body (McNitt-Gray, 1993). Tsiokanos et al. (2002) investigated the relationship between vertical jumping height (squat and countermovement jumps) and the isokinetic moment of force of hip extensors, knee extensors, and ankle plantar flexors in twenty-nine adult males. The subjects performed three maximal isokinetic efforts of the knee extensors, hip extensors, and ankle plantarflexors at angular velocity of 60◦.s–^{1} measured using a Cybex Norm Dynamometer. The authors found that there was a positive relationship between vertical jumping height and total work, and knee and hip extension moments, while a low correlation was found between jumping performance and the isokinetic moment of the ankle plantar flexors.

Force generation has also been investigated in a study by West et al. (2011); the authors included thirty-nine professional rugby league players. After forty-eight hours of trial familiarisation, the participants applied a maximal IMTP with approximately 120-130˚ bend at the knee, and CMJ. Force-time data were processed for PF, peak RFD, and force at 100 milliseconds (F100ms). The PF during IMTP was not correlated to dynamic performance; however, when normalising the data to body weight, it moderately correlated with CMJ height. In addition, moderate correlations were found between peak RFD during IMTP and CMJ height. The F100ms during IMTP was not related to CMJ height; however, when normalising the data of the F100ms to body weight, it was moderately correlated to CMJ height. Therefore, this study provides evidence that values of maximal strength and explosiveness from isometric force-time data are correlated to jump performance in professional rugby league players. In a study by Kawamori et al. (2006), the aim was to examine the relationship between IMTP force-time dependent variables and the force characteristics of vertical jump performances using a standard testing protocol. The data indicates that PF values of IMTP were strongly correlated with PF, peak RFD, and peak power of CMJ. However, peak RFD of IMTP had no correlations with vertical jump performances. Another study by McGuigan et al. (2010) aimed to determine the relationship between measures of the IMTP force characteristics, which were PF and maximum RFD with vertical jump performance (height), in recreationally trained men. The results indicate that there were very strong correlations between VJ height and isometric mid-thigh pull PF. However, there were no correlations with maximum RFD values. This study concludes that the PF during IMTP provides an efficient method for assessing vertical jump height in recreationally trained individuals. Another study by Khamoui et al. (2011) was carried out to investigate the association between the isometric force-time characteristics during IMTP and vertical jump height in nineteen recreationally trained men. Isometric force-time characteristics include PF relative to body mass and RFD at various time frames (IsoRFD50, 100, 150, 200, and 250 milliseconds). This study concludes that PF value is strongly correlated with vertical jump height, while no associations were found between RFD, for all the various time frames (IsoRFD50, 100, 150, 200, and 250 milliseconds), and vertical jump height performance.

It has been reported that almost 80% of ACL injuries that occur are non-contact in nature (Renstrom et al., 2008), such as landing from a high hop, cutting movements, or decelerating in an activity. Knee valgus has been defined as ‘the position or motion of the distal femur towards the midline and the distal tibia away from the midline of the body’ (Hewett et al., 2005 pg.495). Knee valgus might be seen as a possible factor in noncontact ACL injuries (Hewett et al., 2005). The peak knee valgus could contribute towards an increased risk of knee injuries (Heitz et al., 1999; Ireland, 1999). Knee valgus misalignment has been reported to be a common postural dysfunction in the lower extremity during weight bearing exercise, such as SLHL and SLS. The SLS has potential as a functional test, as it is a dynamic movement that is utilised in many daily activities (DiMattia et al., 2005). An example of activities which include the SLS action are landing, stair climbing or running (eccentric knee flexion in a weight-bearing position), and if they are more dynamic, they require more muscle control. However, Zeller et al. (2003) explain that increased knee valgus angle during SLS movement makes it reasonable to believe that other actions, such as deceleration or landing, will be even less controlled.

Therefore, the aim of this chapter is to investigate the relationship between all of the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks in a healthy population. In addition, it will provide the reference values that are needed for each of the individual tests.

5.3 Study Hypotheses (H)

Four hypotheses have been formulated based on the review of the literature:

H1. There are relationships between hop performance tests and 2-D FPPA tests during squat and single-leg horizontal hop land tests.

H2. There are relationships between hop performance tests and balance tests during static and dynamic phases.

H3. There are relationships between hop performance tests and force generation tests during different vertical hop tests and IMTP test.

H4. There are relationships between hop performance tests and isokinetic muscle testing, which includes hip extensors, quadriceps, hamstring, and ankle plantar flexor muscles during both concentric and eccentric muscle actions.

5.4 Methods

5.4.1 Participants

65 Recreationally active healthy students, undergraduate and postgraduate, from the Applied Sports Science and Physiotherapy programmes, as well as Sport Rehabilitation courses, were recruited to take part in the study: 34 males and 31 females, (age 32.34 ± 4.69 years; height 171.09 ± 5.98 cm; and mass 78.81 ± 16.52 kg). Subjects were physically active and had attended at least 30 minutes of physical activity three times a week on a regular basis over the last six months (Munro and Herrington, 2011). Table 5.1 below presents descriptive statistics for the characteristics of these participants. Mean and standard deviation for age, height and weight of the participants is also summarised.

Table 5.1. Demographic data for all participants (N=65)

	Range		**Mean**	**Standard Deviation**
	Minimum	Maximum		
Age (Years)	20	41	32.34	4.69
Height (Centimetres)	157	179	171.09	5.98
Weight (Kilograms)	53.2	126	78.81	16.52

5.4.1.1 Inclusion Criteria

1. Healthy participants able to stand, bend their legs, hop, and land independently
2. Over 18 years of age
3. Able to give informed consent

5.4.1.2 Exclusion Criteria

1. Subjects with pathology or pain in a lower limb affecting standing, bending legs, and hopping or landing ability
2. Lower-limb injury during the last year
3. Lower-limb deformities
4. Unable to give informed consent

Before participation, each subject read the information sheet and signed informed consent form which was approved by the Research, Innovation and Academic Engagement Ethical Approval Panel at the University of Salford (Appendix A).

5.4.2 Facilities and Resources

The experimental procedures were conducted in two laboratories, which are the Human Performance Laboratory and the Strength and Conditioning Laboratory at the University of Salford. All equipment required for the research was already available within the Directorate of Sport. Therefore, no funding was needed for the testing. The study analysis and results have remained anonymous and confidential and are only able to be accessed by the researcher.

5.4.3 Procedure

For each participant, the measurements of the performance of all five different tests were undertaken on the right leg as there were no differences found between the results of the right and left leg tests (symmetry between limbs exists), as shown in the previous chapter (Chapter 4). Subjects were asked to wear their own training shoes- the ones they wear the majority of the time for their training activities. The participants performed one experimental test on the same day they attended. A two minute rest period was given in between each test (Corriveau et al., 2000), with half a minute rest between trials. All subjects were asked not to perform any exercise during the 24 hours prior to testing day, and also not to eat one hour before the testing session (Munro and Herrington, 2011).

The tests were:

1. <u>Hop Tests:</u>

A. Single-leg horizontal hop for distance test
B. Single-leg crossover hop test

2. **2-D FPPA:**
   - A. SLS
   - B. Single-leg horizontal hop for distance
3. **Balance Tests:**
   - A. Straight leg (sway area)
   - B. Bent (30˚) leg (sway area)
   - C. Single-leg horizontal hop land (TTS)
4. **Force Generation Tests:**
   - A. Squat hop
   - B. Countermovement hop
   - C. Ten consecutive hops
   - D. Isometric mid-thigh pull
5. **Isokinetic Muscle Tests:**
   - A. Quadriceps muscle
   - B. Hamstring muscle
   - C. Ankle plantar flexor muscles
   - D. Hip extensor muscles

The procedure has been previously mentioned and explained in detail in the methods chapter (Chapter 2).

5.4.4 Statistical Analysis

All statistical analyses were performed using SPSS software (v. 21, SPSS Inc., Chicago, IL). Descriptive analysis (mean and standard deviation) for each dependent variable was performed. All data were tested for normality using a Shapiro-Wilk test to check whether the data were normally distributed or not (parametric or non-parametric); values were not normally distributed if they were equal to or less than ≤ 0.05 (p-value was set at 0.05). The mean value of the three measures (trials) for each test was calculated and then used to find correlations. Pearson's correlation coefficient (r) was used for parametric data to explore the relationships between all of the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks. Relationships, including nonparametric variables, were tested using Spearman's rank correlation (ρ). Moreover, the coefficient of determination (R^2) was used for the parametric data to determine the amount of variability in one screening test, which has been illustrated by a second screening test (Swearingen et al., 2011). To avoid type I error, Bonferroni correction was used (p-value adjustment) because the test has been applied as part of a cohort comprising *c* tests (Abdi, 2010). The *p* values in this study have been corrected with the Bonferroni approach, and the Bonferroni corrected *p* values for *c* comparisons, denoted *p* Bonferroni, *c* becomes:

p Bonferroni, $c = c \times p$, and corrected *p* values greater than one are set equal to one (Abdi, 2010). The significant *p* values for hop tests were multiplied by two, and for balance tests were multiplied by three. In addition, for dynamic force generation tests (squat hop, countermovement hop, and ten consecutive hops) the significant *p* values were multiplied by four, while for IMTP force generation test and isokinetic muscle strength tests the significant *p* values were multiplied by six. The interpretation of the strength of correlation coefficients used in this study is explained in Table 5.2 below (Hopkins et al., 2009). Force data was normalised to body weight, and hop data was normalised to leg length, as explained in depth in the data processing and analysis section in the methods chapter (Chapter 2).

Table 5.2. Correlation coefficient scores and levels of association (Hopkins et al., 2009)

Correlation Coefficient Score	Level of Association
(0.1–0.3)	Weak
(0.3–0.5)	Moderate
(0.5–0.7)	Strong
(0.7–0.9)	Very Strong
(0.9–1.0)	Extremely Strong

5.5 Results

Normality checking findings for all tests, including all variables, were performed and are listed in Appendix D. Table 5.3 below shows the descriptive statistics for all collated data, including the mean and standard deviation for each variable. Furthermore, it provides a summary of normal values for all the tests in a healthy population.

Table 5.3. Data collected from all the tests (N=65)

Tests				Mean	Standard Deviation
Hop	Single-leg Hop for Distance (%leg length)			133.91	25.89
	Crossover Hop (%leg length)			407.78	94.55
2-D	Squat (FPPA ˚)			8.03	4.93
	Hop Land (FPPA ˚)			7.75	5.00
Balance	Straight Leg (cm^2)			1.20	0.37
	Bent Leg (cm^2)			1.17	0.45
	Hop Land (TTS) (sec)			0.389	0.053
Force	Squat Hop	Max RFD (N·sec/kg)		85.18	32.12
		Peak Force (N/kg)		19.43	3.22
		Peak Power (W/kg)		23.88	4.52
		Peak Velocity ($m·s^{-1}$)		1.56	0.21
Force	Countermovement Hop	Max RFD (N·sec/kg)		80.96	33.20
		Peak Force (N/kg)		19.24	3.72
		Peak Power (W/kg)		25.28	4.93
		Peak Velocity ($m·s^{-1}$)		1.69	0.25
Force	Ten Consecutive Hops	Max RFD (N·sec/kg)		96.19	24.13
		Peak Force (N/kg)		18.15	4.21
		Peak Power (W/kg)		21.35	4.73
		Peak Velocity ($m·s^{-1}$)		1.46	0.25
Force	IMTP	Max RFD (N·sec/kg)		44.86	14.69
		Peak Force (N/kg)		20.20	4.25
		Impulse 0-100 ms (Ns/kg)		0.995	0.061
		Impulse 0-200 ms (Ns/kg)		2.004	0.145
		Impulse 0-250 ms (Ns/kg)		2.538	0.206
		Impulse 0-300 ms (Ns/kg)		3.109	0.291
Isokinetic	Quadriceps	Peak TQ (N·m)	Concentric	187.74	58.25
			Eccentric	221.93	66.80
		Pk TQ/BW (%)	Concentric	240.63	64.52
			Eccentric	284.69	77.00
		Work/BW (%)	Concentric	162.62	49.53
			Eccentric	188.61	55.10
Isokinetic	Hamstring	Peak TQ (N·m)	Concentric	138.17	34.70
			Eccentric	146.22	36.03
		Pk TQ/BW (%)	Concentric	177.55	44.70
			Eccentric	188.45	43.68
		Work/BW (%)	Concentric	131.34	57.42
			Eccentric	134.49	39.01
Isokinetic	Ankle Plantar flexors	Peak TQ (N·m)	Concentric	193.00	53.80
			Eccentric	214.33	56.37
		Pk TQ/BW (%)	Concentric	247.98	63.90
			Eccentric	274.50	66.51
		Work/BW (%)	Concentric	108.07	42.26
			Eccentric	135.96	45.76
Isokinetic	Hip Extensors	Peak TQ (N·m)	Concentric	147.08	51.07
			Eccentric	164.71	47.74
		Pk TQ/BW (%)	Concentric	189.09	62.70
			Eccentric	211.03	58.75
		Work/BW (%)	Concentric	161.79	85.75
			Eccentric	203.12	61.37

(Peak TQ) Peak torque; (Pk TQ/BW) Peak torque to body weight;

(Work/BW) Work to body weight.

Table 5.4 below shows the correlation between all the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests), and hop performance during single-leg hop for distance and crossover hop tasks, in a healthy population. The results indicate that there were no correlations found between hop performance (single-leg hop and crossover hop for distance) and 2-D FPPA angles during squat and single-leg horizontal hop land tasks. For the same results, no correlations were also found between hop performance (single-leg hop and crossover hop for distance) and balance performance during straight leg, bent leg 30˚, and single-leg horizontal hop land tasks. Several correlations were found, however, between the hop performance (single-leg hop and crossover hop for distance) and force generation tests, and these correlations are explained in the following paragraphs. For the dynamic force generation tests (squat hop, countermovement hop, and ten consecutive hops), maximum RFD values in all of these tests show no association with both hop tests. For the squat hop test, there were moderate to strong correlations found between both PF and peak power values during squat hop and hop performance (single-leg hop and crossover hop for distance) ranging between $\rho = 0.32$ and $\rho = 0.56$, and there were strong relationships between the squat hop peak velocity and both hop tests ranging from $r = 0.55$ to $r = 0.57$. In the countermovement hop test, there were moderate to strong relationships between PF, peak power, and peak velocity during countermovement hop, and both hop tests ranging from $r = 0.33$ to $r = 0.67$. In ten consecutive hops test, there were moderate to strong relationships between the PF, peak power, and peak velocity during ten hops force test and both hop tests ranging from $r = 0.44$ to $r = 0.60$. For the static force generation test (IMTP), there were moderate to strong relationships between the maximum RFD and PF during IMTP and both hop tests ranging from $r = 0.33$ to $r = 0.52$; while the impulse values from 0-100, 200, 250, and 300 ms failed to show any associations with hop performance. For the isokinetic muscle tests, the hamstring and hip extensor muscles failed to show any association with either hop for distance test (single-leg hop and crossover hop). For the quadriceps muscle, there was a moderate relationship between total work to body weight during concentric muscle contraction and single-leg hop distance ($r = 0.43$), while a strong relationship found with crossover hop distance ($r = 0.52$). For ankle plantar flexors muscles, there were moderate relationships between peak torque to body weight values, and total work to body weight values, during the concentric and eccentric muscle actions and both hop tests ranging from $r = 0.34$ to $r = 0.45$.

Table 5.4. Shows the correlation between all the tests and hop performance in a healthy population (N=65)

Tests				Single Hop		Crossover Hop	
				r/*ρ* Value (*P* Value)	R^2	*r*/*ρ* Value (*P* Value)	R^2
2-D	Squat			ρ = -0.03 (0.816)		ρ = 0.01 (0.995)	
	Hop Land			ρ = -0.09 (0.456)		ρ = -0.17 (0.175)	
Balance	Straight Leg			*r* = -0.08 (0.521)		*r* = 0.07 (0.591)	
	Bent Leg			ρ = -0.04 (0.743)		ρ = -0.11 (0.371)	
	Hop Land (TTS)			*r* = -0.08 (0.527)		*r* = 0.06 (0.645)	
Force	Squat Hop	Max RFD		ρ = 0.05 (0.719)		ρ = 0.16 (0.193)	
		Peak Force		ρ = 0.32 (0.044)*†		ρ = 0.45 (0.001)*†	
		Peak Power		ρ = 0.41 (0.004)*†		ρ = 0.56 (0.000)*†	
		Peak Velocity		*r* = 0.55 (0.000)*†	0.30	*r* = 0.57 (0.000)*†	0.33
Force	Countermovement Hop	Max RFD		ρ = 0.22 (0.084)		ρ = 0.03 (0.796)	
		Peak Force		ρ = 0.48 (0.000)*†		ρ = 0.33 (0.028)*†	
		Peak Power		ρ = 0.67 (0.000)*†		ρ = 0.61 (0.000)*†	
		Peak Velocity		ρ = 0.63 (0.000)*†		ρ = 0.65 (0.000)*†	
Force	Ten Consecutive Hops	Max RFD		*r* = 0.25 (0.100)†		*r* = 0.22 (0.085)	
		Peak Force		*r* = 0.46 (0.001)*†	0.21	*r* = 0.50 (0.000)*†	0.25
		Peak Power		*r* = 0.44 (0.001)*†	0.19	*r* = 0.49 (0.000)*†	0.24
		Peak Velocity		*r* =0.47 (0.000)*†	0.22	*r* = 0.60 (0.000)*†	0.36
Force	IMTP	Max RFD		ρ = 0.33 (0.042)*†		ρ = 0.40 (0.006)*†	
		Peak Force		ρ = 0.35 (0.030)*†		ρ = 0.52 (0.000)*†	
		Impulse 0-100 ms		ρ = 0.03 (0.834)		ρ = -0.05 (0.667)	
		Impulse 0-200 ms		ρ = 0.09 (0.501)		ρ = -0.07 (0.584)	
		Impulse 0-250 ms		ρ = 0.10 (0.450)		ρ = -0.03 (0.840)	
		Impulse 0-300 ms		ρ = 0.12 (0.326)		ρ = 0.12 (0.357)	
Isokinetic	Quadriceps	Peak TQ	Concentric	ρ = 0.01 (0.981)		ρ = -0.01 (0.963)	
			Eccentric	*r* = -0.01 (0.929)		*r* = -0.10 (0.446)	
		Pk TQ/BW	Concentric	*r* = 0.17 (0.175)		*r* = 0.15 (0.234)	
			Eccentric	*r* = 0.17 (0.177)		*r* = 0.09 (0.468)	
		Work/BW	Concentric	*r* = 0.43 (0.003)*†	0.18	*r* = 0.52 (0.000)*†	0.27
			Eccentric	ρ = 0.26 (0.100)†		ρ = 0.22 (0.076)	
Isokinetic	Hamstring	Peak TQ	Concentric	ρ = 0.08 (0.526)		ρ = 0.01 (0.954)	
			Eccentric	ρ = 0.04 (0.727)		ρ = 0.01 (0.912)	
		Pk TQ/BW	Concentric	*r* = 0.29 (0.100)†		*r* = 0.21 (0.101)	
			Eccentric	ρ = 0.27 (0.100)†		ρ = 0.21 (0.087)	
		Work/BW	Concentric	ρ = 0.24 (0.057)		ρ = 0.23 (0.072)	
			Eccentric	ρ = 0.22 (0.086)		ρ = 0.14 (0.261)	
Isokinetic	Ankle Plantar flexors	Peak TQ	Concentric	*r* = 0.20 (0.105)		*r* = 0.19 (0.122)	
			Eccentric	*r* = 0.19 (0.125)		*r* = 0.13 (0.296)	
		Pk TQ/BW	Concentric	*r* = 0.38 (0.012)*†	0.15	*r* = 0.40 (0.006)*†	0.16
			Eccentric	*r* = 0.36 (0.018)*†	0.13	*r* = 0.34 (0.030)*†	0.12
		Work/BW	Concentric	*r* = 0.40 (0.006)*†	0.16	*r* = 0.45 (0.001)*†	0.20
			Eccentric	*r* = 0.38 (0.012)*†	0.14	*r* = 0.36 (0.018)*†	0.13
Isokinetic	Hip Extensors	Peak TQ	Concentric	ρ = -0.07 (0.608)		ρ = -0.19 (0.126)	
			Eccentric	ρ = -0.11 (0.390)		ρ = -0.25 (0.100)†	
		Pk TQ/BW	Concentric	ρ = 0.04 (0.784)		ρ = -0.07 (0.560)	
			Eccentric	ρ = 0.01 (0.914)		ρ = -0.07 (0.591)	
		Work/BW	Concentric	ρ = 0.03 (0.792)		ρ = 0.26 (0.100)†	
			Eccentric	ρ = 0.01 (0.921)		ρ = 0.07 (0.601)	

(*ρ*) Spearman and (*r*) Pearson correlation coefficients; (R^2) Coefficient of determination; (*) Statistically significant; (†) Bonferroni corrected *p* values; (Peak TQ) Peak torque; (Pk TQ/BW) Peak torque to body weight; (Work/BW) Work to body weight.

5.6 Discussion

The aims of this study were:

1. To investigate the relationship between all of the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks in a healthy population.

2. To provide the reference values that are needed for each of the individual tests.

As explained in the results, there was no relationship found between 2-D FPPA (from SLS and single-leg hop land) and hop performance. Although these correlations would appear hypothetically to be important to hop performance, no previous study has investigated such relationships and, therefore, further investigations are needed in this area to confirm the findings.

For balance tests, there were also no associations found between both balance tests (static and dynamic) and hop performance, and this has been confirmed by Hamilton et al. (2008) who evaluated the relationship between the subject's performance in a THD test and balance tests using the Balance Error Scoring System (BESS); they concluded that the THD is not associated with the BESS test score. Moreover, they evaluated the relationship between the subject's performance during the vertical jump height and balance tests using the Balance Error Scoring System (BESS), which concluded that the vertical jump height is also not associated with the BESS test. However, the participants were asked to wear shoes for the THD test but not for the BESS, which may have resulted in a possible error in comparing both tests, as different surfaces were used. Other research carried out by Tveter and Holm (2010) investigated the influence of balance performance on hop distance in a single-leg hop task. This study reported a weak association between a static balance test and hop distance. However, the static balance performance test in their study was implemented by achieving 30 seconds in two trials on each leg using the KAT 2000, while in the current study it was for 10 seconds in a total of three trials; also, their hop distance was tested twice for each leg using the GAITRite system, while in the current study a normal metric tape measure was used to determine the three trials. However, in their study no practice trials were carried out before each of the individual tests and this may invalid the final results because of the learning effect. Furthermore, in Phillips and van Deursen's (2008) study, a strong correlation was found between time to stability (TTS) when utilising COP excursion (TTS-COP) and hop distance with ACLD participants, but not with healthy subjects (r = 0.55 and r = - 0.02 respectively), and this is similar to the correlation result in the current study between TTS from hop land task and single-leg hop for distance test (*r* = - 0.08) for a healthy population. The authors recommend that ACLD participants may use another technique to complete the task. As a result of the lack of published papers investigating these associations, and due to several balance tests reported in the literature using different methodologies, the final conclusion on the relationship between hop distance test and balance performance is still difficult to provide and requires further investigation.

For the force production test during different vertical hop activities and IMTP, there were several positive relationships found between these tests and hop distance, as illustrated earlier. Although no previous studies have investigated these relationships, some studies have explored similar ones. For example, West et al. (2011) investigated force generation in thirty-nine professional rugby league players. After forty-eight hours of trial familiarisation, the participants applied a maximal IMTP with approximately 120-130° bend at the knee, and CMJ. They found that the PF value during IMTP was moderately correlated to dynamic performance (CMJ height) (*r* = 0.45), and this is quite similar to the finding in the current study for single-leg hop for distance correlation (*r* = 0.35), although a different task was used in the current study, which was a single-leg hop for distance, whereas they used a vertical jump height performance test. In addition, they found moderate correlations between peak RFD during IMTP and CMJ height (*r* = 0.39), and this finding is very close to what was found with the single-leg hop for distance correlation, which was (*r* = 0.33). The F100ms during IMTP in their study was moderately correlated to CMJ height, however current study failed to find such a correlation with both hop tests. Therefore, this may provide evidence that values of maximal strength and explosiveness from isometric force-time data are correlated to jump performance in a healthy population. Another study by Khamoui et al. (2011) investigated the association between the isometric force-time characteristics during IMTP and vertical jump height in nineteen recreationally trained men. Isometric force-time characteristics include PF relative to body mass and RFD at various time frames (IsoRFD50, 100, 150, 200, and 250 milliseconds). This study concluded that PF value is strongly correlated with vertical jump height (*r* = 0.61), which is higher than what has been found in the current study for single-leg hop for distance correlation (*r* = 0.35); while they found no associations between RFD for all the various time frames (IsoRFD50, 100, 150, 200, and 250 milliseconds) and vertical jump height performance, which is similar to what has been found in this study for both hop tests, that is, no correlations were found between impulses for all the various time frames (impulse 0-100, 200, 250, and 300 ms) and both hop tests. Another study by Mcguigan et al. (2010) aimed to determine the relationship between measures of the IMTP force characteristics, which are PF and maximum RFD, with VJ performance (height) in recreationally trained men. The results indicate that there were very strong correlations found between VJ height and IMTP PF. However, there were no correlations with maximum RFD values, and their study concludes that PF during IMTP provides an efficient method for assessing VJ height in recreationally trained individuals.

For isokinetic muscle tests, there was a moderate association found between the quadriceps muscle total work to body weight during concentric muscle contractions and single-leg hop for distance (r = 0.43), and strong correlations found with crossover hop for distance (r = 0.52). A similar correlation was found by English et al. (2006), who report a strong correlation between quadriceps total work to body weight during concentric muscle contraction and single-leg hop for distance (r = 0.56) using the same speed of 60 degrees/sec for isokinetic muscle testing for 30 healthy subjects. Another study by Pincivero et al. (1997) reports a relationship between single-leg hop for distance test and isokinetic total work to body weight for the quadriceps muscles (r = 0.44) at a speed of 60 degrees/sec. The same association has also been confirmed by Noyes et al. (1991), who have reported a moderate relationship between quadriceps muscle strength measures and single-leg hop tests in sixty-seven participants (r = 0.49). However, Noyes et al. (1991) carried out the tests with ACL deficient patients, meaning it is different to the group (healthy) in the current study. In addition, their study found a relationship between quadriceps muscle strength and single-leg hop for the distance test only, and not for the crossover hop test, which makes a comparison with the crossover hop test results almost impossible because of the lack of any previous correlation studies. Ankle plantar flexors peak torque to body weight and total work to body weight values during concentric and eccentric muscle actions were moderately correlated to both hop tests (single-leg hop for distance and crossover hop). This has been confirmed by Tsiokanos et al. (2002) who investigated the relationship between vertical jumping height (squat and countermovement jumps) and isokinetic moment of force of ankle plantar flexors in twenty-nine adult males. The subjects performed three maximal isokinetic efforts with the ankle plantar flexors at an angular velocity of $60^{\circ}.s^{-1}$ using a Cybex Norm Dynamometer. Although different methods were used in their study, which involved vertical jump performance, they found that there was a weak correlation between jumping performance and the isokinetic moment of the ankle plantar flexors. In the current study hamstring and hip extensor muscles failed to show any association with hop performance. Although previous studies have revealed that there are associations between both hamstring and hip extensor muscles with hop performance (Noyes et al., 1991; Tsiokanos et al., 2002), the different methodologies used with different tools may explain the differences.

Therefore, and from the above discussion, force generation is considered as a contributing factor in hop performance, although not a strong predictor, based on the coefficient of determination values presented in table 5.4. Additionally, ankle plantar flexors muscle strength during both the take-off phase (concentric) and landing phase (eccentric) are also critical to hop performance in a recreationally active healthy population. The relationships also seemed stronger when undertaking multiple hops (i.e. crossover hop test) and then a single hop, which may be related to the greater plyometric (muscle stretch-shorten) action. In addition, the current findings can suggest that hop tests can be used in a clinic to indicate potential deficits in strength or force generation in lower limbs in a healthy population, however, not with overall balance and lower limb alignment. Therefore, lower limb balance and alignment should not be taken into considerations when evaluating hop performance in the future. It is not surprising that multi-joint assessment of force production was more closely related to multi-joint hopping tasks when compared to the single joint isokinetic testing, as previous research has shown weak correlations between single joint assessment of force and athletic tasks (Blackburn and Morrissey, 1998).

While the single hop and cross-over hop distances in this chapter are lower than those previously reported (Munro and Herrington, 2011) this is likely due to the differences in training status and therefore relative strength of the subjects. Given the relationships between force production and hop performances highlighted above.

One possible limitation is that regression analysis was not performed in this chapter, however as all variables were linked to force production (e.g. force is highly correlated with RFD and power) it was not considered necessary as each of these force-time variables is inextricably linked.

5.7 Conclusion

This study has aimed to investigate the relationship between all of the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks in 65 healthy participants, and provide the reference values that are needed for each of the individual tests. Several positive correlations have been found between force production tests and hop performance (single-leg hop for distance and crossover hop), apart from the impulses at all various time frames (impulse 0-100, 200, 250, and 300 ms), which do not show any association. Moreover, positive correlations have been found between quadriceps muscle total work to body weight during concentric muscle contraction and both hop performance tests. The same positive correlations have been found between ankle plantar flexors peak torque to body weight and total work to body weight values, during concentric and eccentric muscle action and both hop performance tests, whilst other tests fail to show any association with hop performance. The relationships also seemed stronger when undertaking multiple hops (i.e. crossover hop test) and then a single hop. These findings can conclude that force generation and ankle plantar flexion strength seem to be the most contributing factors to hop performance. Also, hop tests can be used in a clinic to identify potential deficits in strength or force generation in lower limbs in a healthy population.

Chapter (6)

The Relationship Between all the Tests and Hopping Performance in ACL Reconstructed Participants

6 Chapter 6: The Relationship Between all the Tests and Hopping Performance in ACL Reconstructed Participants

6.1 Aims

1. To investigate the differences between injured and non-injured leg performance across all tests, which includes hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic muscle tests in ACL reconstructed participants.

2. To describe the reference values for LSI for hop tests and isokinetic muscle tests in ACL reconstructed participants.

3. To investigate the relationship between all of the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks for the injured and non-injured limbs in ACL reconstructed participants.

4. To provide the reference values that are needed for each of the individual tests for both the injured and non-injured limbs in ACL reconstructed participants.

6.2 Background

As explained in the previous chapter, hopping is a common task performed in many sports, and in landing from some tasks, the impact forces produced can reach a magnitude of up to twelve times the body weight (Perttunen et al., 2000) and result in injuries to the lower extremities (Jacobs et al., 2007). Landing involves strong forces being applied by the knee and hip extensors and ankle plantar flexors to control joint flexion and decelerate the body (Mcnitt-Gray, 1993). When landing, the lower extremities help to absorb and dissipate the ground reaction forces resulting from each hop. If these forces are very strong and the body cannot accommodate and control them, there is a risk of injury. Research has been conducted on jumping to try to understand how one generates and uses the energy needed to push oneself. In studies of landing, there has been a concentration on the biomechanical implications of impact, and of the total load on lower limb tissues (Devita and Skelly, 1992). However, during different activities, the landing phase may be overlooked, which might contribute towards poor performance or injury. Thus, there has been an increased focus on the factors that contribute to different hop and landing techniques (Dufek and Bates, 1991), especially in ACL reconstructed patients. Many studies have confirmed that hop tests are able to reflect functional limitations in the lower extremities; however, their ability to discover specific deficiencies remains unclear (Barber et al., 1990; Noyes et al., 1991). DeCarlo et al. (1999) assessed athletes who had undertaken anterior cruciate ligament surgery, using the single-leg hop for distance test six and 10 weeks after surgery, to assess the progress made during rehabilitation. They found that athletes achieved relatively good scores for a single-leg hop for distance test when comparing the involved leg results with the non-involved limb.

Most rehabilitation programmes use some form of testing to determine the readiness to return to sport or to determine the functional limitation of the lower limbs; however, it is important to determine what the pass criteria is. One of the most common return to sport criteria reported in the literature is 85% to 90% on the limb symmetry index (LSI). Munro and Herrington (2011) found that the average LSI for the four hop tests (single, triple, crossover, and 6 meters timed hop) was 100 percent (98.38 - 101.61 %.) and that 100 percent of healthy participants have at least an LSI of 90%. Therefore, and based on Munro and Herrington’s (2011) results, researchers/ practitioners advocate that the return to sport LSI criteria for hop tests should be increased to 90% from the previously recommended 85% (Noyes et al., 1991). In chapter four in the current thesis, the LSI findings regarding crossover hop test were mainly in common with Munro and Herrington’s (2011) results that 100 percent of healthy participants have at least an LSI of 95%, while for single-leg hop for distance test the findings were 100 percent of healthy participants have at least an LSI of 85%. Petschnig et al. (1998) found that for ACL reconstructed patients, the average LSI for a single-leg hop test was 85% one year post-operative. Furthermore, the same authors found the same percentage (85%) of LSI for quadriceps isokinetic muscle strength tests with the same group of ACL reconstructed patients using Cybex 6000.

Some researchers have used the LSI to determine the sensitivity and specificity of hop tests for detecting deficits in lower extremity functioning in patients with ACL deficiency (Noyes et al., 1991); the underlying assumption in their study is that the detection of an abnormal LSI would specify the presence of a functional deficit. Generally, the researchers found that using a combination of single-leg hop tests to determine abnormal LSI was more sensitive than utilising any one hop test in isolation. However, in Noyes et al. (1991) study, a significant number of patients with ACL deficiency had normal LSI for the hop tests. Moreover, it is unclear whether abnormal or normal LSI are well associated with a patient's overall functional ability. For this reason, to make hop tests useful for assessing deficits in lower limb function, it is essential to know how hop tests are associated with other measures of impairment and function, as well as how accurately hop tests can predict which patients are ready to return to sports and which patients are at risk of continued problems with functional instability (Fitzgerald et al., 2001).

Hop tests have been used previously to detect changes in functional status in response to a knee rehabilitation program (Fitzgerald et al., 2000). In the previous study, the data demonstrates that performance on hop tests mainly improves concomitantly with improvements in other functional outcome measures that have been utilised to reflect changes in functional status in response to rehabilitation programs. Therefore, it would seem reasonable that using hop tests could reflect changes in ACL patients' status in response to treatment. However, there is a lack of information on determining how much change in hop test performance would constitute a clinically meaningful change in response to treatment. Therefore, this study has been carried out to investigate the differences between injured and non-injured leg performance across all tests, which include hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic muscle tests, as well as to describe reference values for the LSI for hop tests and isokinetic muscle tests in ACLR participants. In addition, it has investigated the relationship between all of the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance for the injured and non-injured limbs during single-leg hop for distance and crossover hop tasks in ACLR participants, and provided the reference values that are needed for each of the individual tests for both the injured and non-injured limbs.

6.3 Study Hypotheses (H)

Nine hypotheses were formulated based on the review of the literature:

H1. There is a difference between measurement scores examined in both lower limbs for two hop tests, which are single-leg horizontal hop for distance and crossover hop tests.

H2. There is a difference between measurement scores examined in both lower limbs for 2-D FPPA tests during squat and single-leg horizontal hop land tests.

H3. There is a difference between measurement scores examined in both lower limbs for both static and dynamic balance tests.

H4. There is a difference between measurement scores examined in both lower limbs for force generation tests during both 10 consecutive hops and IMTP tests.

H5. There is a difference between measurement scores examined in both lower limbs for isokinetic muscle testing, which are quadriceps and hamstring muscles, in both concentric and eccentric muscle actions.

H6. There is a relationship between hop performance tests and 2-D FPPA tests during squat and single-leg horizontal hop land tests for both the injured and non-injured limbs.

H7. There is a relationship between hop performance tests and balance tests during static and dynamic phases for both the injured and non-injured limbs.

H8. There is a relationship between hop performance tests and force generation tests during 10 consecutive hops test and IMTP test for both the injured and non-injured limbs.

H9. There is a relationship between hop performance tests and isokinetic muscle testing of knee muscles (quadriceps and hamstring) during both concentric and eccentric muscle actions for both the injured and non-injured limbs.

6.4 Methods

6.4.1 Participants

33 ACL reconstructed participants (6-9 post-operative) from sport clubs (two Taekwondo, six rugby, and 25 soccer players) were invited to take part in the study (see the invitation letter Appendix E), 23 males and 10 females (age 22.55 ± 3.76 years; height 177.55 ± 7.99 cm; and mass 79.97 ± 14.36 kg). The reason behind choosing these sports (Taekwondo, rugby, and soccer) was to make sure that this study provided a homogenous group from different sporting activities including different force and strength characteristics. All the ACLR participants participating in this study have been medically released to return to sport, and can play any kind of sporting activities that is the reason why they have to be between 6-9 post-operative. Table 6.1 below presents the descriptive statistics for the characteristics of these ACL reconstructed participants. The mean and standard deviation for the age, height and weight of the ACL reconstructed participants are also summarised.

Table 6.1. Demographic data for all ACL reconstructed participants (N=33)

	Range		**Mean**	**Standard Deviation**
	Minimum	Maximum		
Age (Years)	18	31	22.55	3.76
Height (Centimetres)	161	193	177.55	7.99
Weight (Kilograms)	59	123	79.97	14.36

6.4.1.1 Inclusion Criteria

1. 6-9 post ACL reconstructed participants (either bone patella bone or hamstring autograft) medically cleared by an orthopaedic surgeon to return to unrestricted activity (sport).

2. Had no other significant injuries at time of ACL injury, meniscal injury requiring repair (meniscectomy can be included); medial collateral injury greater than grade one, any other ligamentous disruption, bony bruising can be included.

3. Are able to run, cut, hop and land without pain or joint irritation.

4. Over 18 years of age.

5. Able to give informed consent.

6.4.1.2 Exclusion Criteria

1. 6-9 post ACL reconstructed participants with any other pathology or pain in a lower limb affecting the ability to move, hop and land, or run.

2. Lower-limb deformities.

3. Unable to give informed consent.

Before participation, each of the ACL reconstructed participants read the information sheet and signed the informed consent form which was approved by the Research, Innovation and Academic Engagement Ethical Approval Panel at the University of Salford (Appendix F).

6.4.2 Facilities and Resources

The experimental procedures were conducted in two laboratories, which are the Human Performance Laboratory and the Strength and Conditioning Laboratory at the University of Salford. All equipment required for the research was already available within the Directorate of Sport. Therefore, no funding was needed for the testing. The study analysis and results have remained anonymous and confidential, and only able to be accessed by the researcher.

6.4.3 Procedure

For each ACL reconstructed participant, the measurements of the performance of all five different tests were undertaken for both legs (the injured and non-injured limbs). ACL reconstructed participants were asked to wear their own training shoes, with these shoes being the ones they wear the majority of the time for their training activities. ACL reconstructed participants participated in one experimental test on one day. A two minute rest period was given in between each test (Corriveau et al., 2000), with half a minute rest between trials. All ACL reconstructed participants were asked not to perform any exercise in the 24 hours prior to testing day, and also not to eat one hour before testing session (Munro and Herrington, 2011).

The tests were:

1. <u>Hop Tests:</u>

   A. Single-leg horizontal hop for distance test
   B. Single-leg crossover hop test

2. **2-D FPPA:**
    - A. SLS
    - B. Single-leg horizontal hop land
3. **Balance Tests:**
    - A. Straight leg (sway area)
    - B. Bent (30˚) leg (sway area)
    - C. Single-leg horizontal hop land (TTS)
4. **Force Generation tests:**
    - A. Ten consecutive hops
    - B. Isometric mid-thigh pull
5. **Isokinetic Muscle Tests:**
    - A. Quadriceps muscle
    - B. Hamstring muscle

The procedure has been previously mentioned and explained in detail in the methods chapter (Chapter 2). However, two tests were excluded from the force tests, which are the squat hop and countermovement hop, as well as two tests being excluded from isokinetic muscle testing, which are hip extensor and ankle plantar flexor muscle testing. The first reason behind excluding these tests is because these tests were taking a long time with the healthy participants during their examinations (greater than 2 hours), therefore, to avoid any fatigue that might occur to ACL reconstructed participants during their evaluations, these tests were taken out. The second reason was the limited time for ACL reconstructed participants to participate in the study (maximum of two hours). For the force tests, the two tests chosen were ten consecutive hops and IMTP, and this was just to make sure that the ACL reconstructed participants undertook one dynamic force test, which was the 10 consecutive hops, and one static force test- the IMTP. In order to make sure that there were correlations between the ten consecutive hops test and both the excluded tests, which are the squat hop and countermovement hop, a correlation between these tests was performed from the results of the previous study that was carried out, as described in the last chapter on a healthy population (65 participants) using the same statistical analysis; the details on all of this is explained in the Table 6.2 below:

Table 6.2. Shows the correlation between the ten consecutive hops test and both the squat hop and countermovement hop tests in a normal population (N=65)

Tests			10 Consecutive Hops	
			r/ρ Value (P Value)	R^2
Force	Squat Hop	Max RFD	$\rho = 0.19$ (0.139)	
		Peak Force	$\rho = 0.43$ (0.000)*	
		Peak Power	$\rho = 0.52$ (0.000)*	
		Peak Velocity	$r = 0.49$ (0.000)*	.240
	Countermovement Hop	Max RFD	$\rho = 0.35$ (0.004)	
		Peak Force	$\rho = 0.39$ (0.001)*	
		Peak Power	$\rho = 0.56$ (0.000)*	
		Peak Velocity	$\rho = 0.61$ (0.000)*	

(ρ) Spearman and (r) Pearson correlation coefficients; (R^2) Coefficient of determination;
(*) Statistically significant

From the above table the results indicate that all variables for the ten consecutive hops test and the variables from both the squat hop and countermovement hop are associated, apart from maximum RFD during the squat hop and ten continuous hops tests not being correlated to each other.

For the isokinetic muscle tests, the two excluded tests were for the hip extensor and ankle plantar flexor muscles. Although it was concluded in the previous chapter (65 healthy correlation chapter) that ankle plantar flexor muscle strength is a critical factor which contributes towards hop performance, the decision for choosing these two muscles (quadriceps and hamstring) was made before attaining these results, because the data collection for both correlation studies of healthy and ACL reconstructed participants was undertaken during an overlapping period of time, prior to analysis of the data from the previous study. Therefore, the main reasons behind choosing the quadriceps and hamstring muscles and excluding the hip extensor and ankle plantar flexor muscles is, as explained earlier, the restricted time for the attendance of the ACL reconstructed participants and to avoid any muscle fatigue that may occur to them during their examinations. Another reason is because it has mainly been reported in previous studies that only the knee muscles, quadriceps and hamstring, are correlated with hop performance and should be taken into consideration with ACL reconstructed patients (Keays et al., 2003; Petschnig et al., 1998; Wilk et al., 1994; Noyes et al., 1991); therefore, these two muscles were chosen to be tested in this study on ACL reconstructed participants.

Additionally, for the crossover hop for distance test, there was also a clinical change in this test with ACL reconstructed participants, as instead of instructing the participant to do three crossover hops, they were instructed to do four crossover hops. The reason behind using four crossover hops was to make sure that there were two equivalent landings, two right and two left, for each leg tested as a difference in number of landings either side of the line may bias the results. It has been explained in the previous chapters that all healthy participants applied the crossover hop test with three landings (as explained in depth in the methods chapter), and in order to make sure that there was a correlation between the three and four crossover hop tests, a relationship study was carried out to discover the association between these two tests; the full details of this study are explained below.

Crossover Hop Correlation Study

20 Recreationally active healthy students from Applied Sports Science and Physiotherapy degree programmes, as well as Sport Rehabilitation courses, were recruited to take part in the study: 10 males and 10 females (age 22.05 ± 2.11 years; height 170.35 ± 4.64 cm; and mass 75.20 ± 7.09 kg). The subjects were physically active and had attended at least 30 minutes of physical activity three times a week on a regular basis over the last six months (Munro and Herrington, 2011). The inclusion criteria was: 1) healthy participants able to stand, bend their legs, hop, and land independently, 2) over 18 years of age, and 3) able to give informed consent. The exclusion criteria was: 1) subjects with pathology or pain in a lower limb affecting standing, bending legs, and hopping or landing ability, 2) lower-limb injury during the last year, 3) lower-limb deformities, and 4) unable to give informed consent. Before participation, each subject read the information sheet and signed the informed consent form which was approved by the Research, Innovation and Academic Engagement Ethical Approval Panel at the University of Salford (Appendix A). The experimental procedures were conducted in the Human Performance Laboratory at the University of Salford. All equipment required for the research was already available within the Directorate of Sport. For each participant, the measurements of the performance for the two different hop tests were undertaken on the right leg as there were no differences found between the results of the right and left leg tests (symmetry between limbs exists), as explained previously in Chapter 4. The subjects were asked to wear their own training shoes, the ones they wear the majority of the time for their training activities. The participants performed one experimental test on one day. A two minute rest period was given in between each test (Corriveau et al., 2000), with half a minute rest between trials. All subjects were asked not to perform any exercise during the 24 hours prior to testing day and also not to eat one hour before the testing session (Munro and Herrington, 2011). The subjects were then asked to perform three and four crossover hop tests, while testing order was randomised.

The full details of the procedure have previously been described and explained in the methods chapter (Chapter 2). The mean value of the three measures (trials) for each test was calculated to find out the correlations. Hop data was normalised to leg length, as explained in depth in the data processing and analysis section in the methods chapter (Chapter 2). Table 6.3 below shows the descriptive statistics for the collated data, including the mean and standard deviation for each test.

Table 6.3. Data collected for the three and four crossover hop tests (N=20)

Tests		**Mean**	**SD**
Hop	3 Crossover hops (cm)	454.57	102.93
	4 Crossover hops (cm)	640.40	142.37

(SD) Standard deviation

All data were tested for normality using a Shapiro-Wilk test to check whether the data were normally distributed or not (parametric or non-parametric); values were not normally distributed if they were equal to or less than ≤ 0.05 (*p*-value was set at 0.05). For full details of these results please see Table 6.4 below:

Table 6.4. Tests of normality for the three and four crossover hop tests

Test		**Shapiro-Wilk**		
		Statistic	Df	Sig.
Hop	3 Crossover hop for distance	0.973	20	0.826
	4 Crossover hop for distance	0.971	20	0.786

Pearson's correlation coefficient (*r*) was used to explore the relationships between both hop tests because the data was normally distributed. Table 6.5 below explains the correlation between both hop tests. The results indicate that there was an extremely strong correlation found between both hop performances (the three and four crossover hop tests).

Table 6.5. Shows the correlation between the three and four crossover hop tests in a healthy population (N=20)

Tests	Pearson Correlation Coefficients		
	r Value	*p* Value	R2
3 & 4 Crossover Hops	0.99*	0.000	0.97

(*r*) Pearson correlation coefficients; (R^2) Coefficient of determination;
(*) Statistically significant

From the above table, it can be concluded that there was an extremely strong correlation found between both hop performances (the three and four crossover hop tests), which means that one test performance can define and explain the other. Therefore, and from the above explanations, four crossover hop tests were used in this study (ACL reconstructed study).

6.4.4 Statistical Analysis

All statistical analyses were performed using SPSS software (v. 21, SPSS Inc., Chicago, IL). Descriptive analysis (mean and standard deviation) for each dependent variable was carried out. All data were tested for normality using a Shapiro-Wilk test to check whether the data were normally distributed or not (parametric or non-parametric); values were not normally distributed if they were equal to or less than ≤ 0.05 (*p*-value was set at 0.05). The mean value of the three measures (trials) for each test was calculated to find out the differences between the injured and non-injured limb performances, also to find out the correlations between both the injured and non-injured limb performances and hop test distances throughout all of the tests. Limb differences were determined using a paired t-test for parametric variables and a Wilcoxon Rank Test for non-parametric variables. The LSI for hop tests and isokinetic muscle strength tests was calculated using the following equation:

LSI = injured leg/ uninjured leg * 100 (Fitzgerald et al., 2001).

Pearson's correlation coefficient (*r*) was used for parametric data to explore the relationships between all of the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks. Relationships, including nonparametric variables, were tested using Spearman's rank correlation (ρ). Moreover, the coefficient of determination (R^2) was used for the parametric data to determine the amount of variability in one screening test, which is illustrated by a second screening test (Swearingen et al., 2011). To avoid type I error, the Bonferroni correction was used (*p*-value adjustment) because the test has been applied as part of a cohort comprising *c* tests (Abdi, 2010). The *p* values in this study were corrected using the Bonferroni approach and the Bonferroni corrected *p* values for *c* comparisons, denoted *p* Bonferroni, *c* becomes:

p Bonferroni, $c = c \times p$, and corrected *p* values greater than one are set equal to one (Abdi, 2010). The significant *p* values for hop tests were multiplied by two, and for balance tests were multiplied by three. In addition, for dynamic force generation tests (squat hop, countermovement hop, and ten consecutive hops) the significant *p* values were multiplied by four, while for IMTP force generation test and isokinetic muscle strength tests the significant *p* values were multiplied by six. The interpretation of the strength of correlation coefficients used in this study is explained in Table 6.6 below (Hopkins et al., 2009). Force data was normalised to body weight, and hop data was normalised to leg length, as explained in depth in the data processing and analysis section in the methods chapter (Chapter 2).

Table 6.6. Correlation coefficient scores and levels of association (Hopkins et al., 2009)

Correlation Coefficient Score	Level of Association
(0.1–0.3)	Weak
(0.3–0.5)	Moderate
(0.5–0.7)	Strong
(0.7–0.9)	Very Strong
(0.9–1.0)	Extremely Strong

6.5 Results

The findings were checked for normality for all the tests, including all variables, and these are listed in Appendix G. Table 6.7 below shows the descriptive statistics for all collated data, including the mean and standard deviation for each variable for both the injured and non-injured limbs. Furthermore, it provides a summary of reference values for all the tests with 6-9 post ACL reconstructed participants. Also, this table shows the differences between injured and non-injured limb performance.

Table 6.7. Data collected from ACL reconstructed participants for all the tests (N=33), and illustrates the differences between injured and non-injured limb performance

Tests				Injured		Non-Injured		
				Mean	SD	Mean	SD	*p* Value
Hop	Single-leg Hop for Distance (%leg length)			171.62	30.58	189.21	25.87	< 0.001*
	Crossover Hop (%leg length)			646.28	136.26	717.83	135.06	0.001*
2-D	Squat (FPPA ˚)			4.09	2.41	4.42	3.67	0.979
	Hop Land (FPPA ˚)			6.04	3.81	5.80	4.84	0.538
Balance	Straight Leg (cm^2)			1.24	0.52	1.24	0.41	0.598
	Bent Leg (cm^2)			1.15	0.46	1.18	0.42	0.401
	Hop Land (TTS) (sec)			0.48	0.12	0.50	0.15	0.386
Force	Ten Consecutive Hops	Max RFD (N·sec/kg)		148.50	38.51	154.01	26.15	0.316
		Peak Force (N/kg)		25.93	6.52	28.05	5.9	0.029*
		Peak Power (W/kg)		32.78	8.62	35.57	7.39	0.058
		Peak Velocity ($m·s^{-1}$)		1.98	0.52	2.11	0.43	0.090
Force	IMTP	Max RFD (N·sec/kg)		108.56	38.76	109.38	38.41	0.859
		Peak Force (N/kg)		25.18	2.85	25.51	2.37	0.354
		Impulse 0-100 ms (Ns/kg)		1.00	0.09	0.99	0.12	0.555
		Impulse 0-200 ms (Ns/kg)		2.12	0.32	2.10	0.28	0.561
		Impulse 0-250 ms (Ns/kg)		2.77	0.50	2.75	0.44	0.808
		Impulse 0-300 ms (Ns/kg)		3.48	0.71	3.45	0.66	0.734
Isokinetic	Quadriceps	Peak TQ (N·m)	Concentric	213.15	76.30	264.65	92.04	< 0.001*
			Eccentric	253.54	101.67	303.02	112.43	< 0.001*
		Pk TQ/BW (%)	Concentric	263.20	63.37	327.40	68.51	< 0.001*
			Eccentric	307.95	88.87	369.94	97.73	< 0.001*
		Work/BW (%)	Concentric	204.73	56.55	241.73	56.99	< 0.001*
			Eccentric	209.40	53.36	263.61	74.62	< 0.001*

Isokinetic	Hamstring	Peak TQ (N·m)	Concentric	154.70	61.60	174.99	67.90	< 0.001*
			Eccentric	158.22	52.62	179.92	59.72	< 0.001*
		Pk TQ/BW (%)	Concentric	192.67	57.10	216.90	58.01	< 0.001*
			Eccentric	196.54	45.74	224.62	49.94	< 0.001*
		Work/BW (%)	Concentric	149.93	48.06	180.44	71.75	0.004*
			Eccentric	161.94	60.90	176.72	73.21	0.189

(Peak TQ) Peak torque; (Pk TQ/BW) Peak torque to body weight;

(Work/BW) Work to body weight; (SD) Standard deviation; (*) $p < 0.05$

Table 6.8 below illustrates the percentage of ACL reconstructed participants achieving LSI values for hop tests and isokinetic muscles tests.

Table 6.8. Percentage of ACL reconstructed participants achieving LSI values for hop tests and isokinetic muscles tests

LSI				≥ 85	≥ 90	≥ 95
Hop	Single-leg Hop for Distance			72.7	63.6	36.4
	Crossover Hop			81.8	63.6	39.4
Isokinetic	Quadriceps	Peak TQ	Concentric	51.5	33.3	15.2
			Eccentric	57.6	39.4	21.2
		Pk TQ/BW	Concentric	42.4	27.3	15.2
			Eccentric	57.6	33.3	24.2
		Work/BW	Concentric	54.5	39.4	27.3
			Eccentric	42.4	33.3	27.3
Isokinetic	Hamstring	Peak TQ	Concentric	57.6	48.5	33.3
			Eccentric	45.5	45.5	30.3
		Pk TQ/BW	Concentric	60.6	54.5	33.3
			Eccentric	48.5	42.4	30.3
		Work/BW	Concentric	51.5	42.4	36.4
			Eccentric	48.5	42.4	39.4

(Peak TQ) Peak torque; (Pk TQ/BW) Peak torque to body weight;

(Work/BW) Work to body weight

Table 6.9 below shows the correlation between all the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks for the injured limb in ACL reconstructed participants. The results indicate that there were no correlations found between hop performance (single-leg hop for distance and crossover hop) and 2-D FPPA angles during squat and maximum single-leg horizontal hop land tasks. The same results of no correlations were also found between hop performance (single-leg hop for distance and crossover hop) and balance performance during straight leg, bent leg 30˚, and single-leg horizontal hop land tasks. Several correlations were found between the hop performance (single-leg hop for distance and crossover hop) and force generation tests during the 10 consecutive hops test, and these correlations are explained in the following paragraphs. There were moderate to strong associations found between single-leg hop for distance values and maximum RFD, peak force, and peak power values during the 10 consecutive hops test ($r = 0.56$, $r = 0.47$, $r = 0.52$, respectively), while these associations were not found with peak velocity value. There were also moderate to strong associations found between crossover hop for distance values and maximum RFD, peak power, and peak velocity values during the 10 consecutive hops test ($r = 0.50$, $r = 0.45$, $\rho = 0.45$, respectively), while these associations were not found with peak force value. No correlations were found between hop performance (single-leg hop for distance and crossover hop) and the variables of the IMTP test. For the isokinetic muscle tests, quadriceps and hamstring muscles were associated with both hop tests (single-leg hop for distance and crossover hop). There were moderate to large associations found between quadriceps concentric peak torque values and both hop performances, single-leg hop for distance and crossover hop, ($\rho = 0.55$, $\rho = 0.46$, respectively). Quadriceps eccentric peak torque value was only associated moderately with single-leg hop for distance ($r = 0.42$). There were strong associations found between quadriceps concentric peak torque to body weight values and both hop performances, single-leg hop for distance and crossover hop, ($r = 0.64$, $r = 0.52$, respectively). Quadriceps eccentric peak torque to body weight value was only associated strongly with single-leg hop for distance ($r = 0.51$). There were moderate associations found between quadriceps concentric work to body weight values and both hop performances, single-leg hop for distance and crossover hop, ($r = 0.46$, $r = 0.47$, respectively), while quadriceps eccentric work to body weight values failed to show any associations with both hop performance tests. For hamstring isokinetic muscle tests, the concentric peak torque value of the hamstring muscle was only moderately associated with single-leg hop for distance ($r = 0.46$). There were moderate to strong associations found between hamstring eccentric peak torque values and both hop performances, single-leg hop for distance and crossover hop, ($\rho = 0.57$, $\rho = 0.48$, respectively). Moreover, there were strong associations found between hamstring concentric and eccentric peak torque to body weight values and both hop performances, single-leg hop for distance and crossover hop, ranging between $r = 0.50$ - $r = 0.69$. Lastly, both concentric and eccentric work to body weight values for the hamstring muscle failed to show any associations with both hop performances.

Table 6.9. Shows the correlation between all the tests and hop performance for the injured limb in ACL reconstructed participants (N=33)

Tests				Single Hop		Crossover Hop	
				r/ ρ Value (P Value)	R^2	r/ ρ Value (P Value)	R^2
2-D	Squat			r = -0.12 (0.523)		r = 0.10 (0.582)	
	Hop Land			r = -0.10 (0.587)		r = -0.10 (0.571)	
Balance	Straight Leg			ρ = 0.30 (0.090)		ρ = 0.19 (0.284)	
	Bent Leg			ρ = 0.25 (0.165)		ρ = 0.15 (0.409)	
	TTS			ρ = -0.01 (0.979)		ρ = 0.03 (0.891)	
Force	10 Hops	Max RFD		r = 0.56 (0.004)*†	0.31	r = 0.50 (0.012)*†	0.25
		Peak Force		r = 0.47 (0.020)*†	0.23	r = 0.36 (0.100)†	
		Peak Power		r = 0.52 (0.008)*†	0.27	r = 0.45 (0.032)*†	0.21
		Peak Velocity		ρ = 0.42 (0.064)†		ρ = 0.45 (0.032)*†	
Force	IMTP	Max RFD		r = -0.01 (0.978)		r = 0.07 (0.703)	
		Peak Force		r = 0.23 (0.206)		r = 0.17 (0.360)	
		Impulse 0-100 ms		ρ = 0.08 (0.655)		ρ = -0.02 (0.932)	
		Impulse 0-200 ms		ρ = -0.25 (0.164)		ρ = -0.28 (0.116)	
		Impulse 0-250 ms		ρ = -0.26 (0.151)		ρ = -0.27 (0.130)	
		Impulse 0-300 ms		ρ = -0.20 (0.269)		ρ = -0.21 (0.247)	
Isokinetic	Quadriceps	Peak TQ	Concentric	ρ = 0.55 (0.003)*†		ρ = 0.46 (0.024)*†	
			Eccentric	r = 0.42 (0.045)*†	0.18	r = 0.28 (0.120)	
		Pk TQ/BW	Concentric	r = 0.64 (0.000)*†	0.41	r = 0.52 (0.006)*†	0.27
			Eccentric	r = 0.51 (0.009)*†	0.26	r = 0.39 (0.072)†	
		Work/BW	Concentric	r = 0.46 (0.021)*†	0.21	r = 0.47 (0.018)*†	0.22
			Eccentric	r = 0.41 (0.051)†		r = 0.32 (0.100)†	
Isokinetic	Hamstring	Peak TQ	Concentric	r = 0.46 (0.021)*†	0.21	r = 0.39 (0.081)†	
			Eccentric	ρ = 0.57 (0.003)*†		ρ = 0.48 (0.015)*†	
		Pk TQ/BW	Concentric	r = 0.57 (0.001)*†	0.33	r = 0.50 (0.009)*†	0.25
			Eccentric	r = 0.69 (0.000)*†	0.47	r = 0.58 (0.001)*†	0.34
		Work/BW	Concentric	r = 0.41 (0.054)†		r = 0.36 (0.100)†	
			Eccentric	r = 0.27 (0.135)		r = 0.22 (0.230)	

(ρ) Spearman and (r) Pearson correlation coefficients; (R^2) Coefficient of determination;

(*) Statistically significant; (†) Bonferroni corrected p values; (Peak TQ) Peak torque;

(Pk TQ/BW) Peak torque to body weight; (Work/BW) Work to body weight.

Table 6.10 below shows the correlation between all the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks for the non-injured limb in ACL reconstructed participants. The results indicate that there were no correlations found between all the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks.

Table 6.10. Shows the correlation between all the tests and hop performance for the non-injured limb in ACL reconstructed participants (N=33)

Tests				Single Hop	Crossover Hop
				r/ *ρ* Value (*P* Value)	*r*/ *ρ* Value (*P* Value)
2-D	Squat			ρ = -0.23 (0.200)	ρ = -0.13 (0.465)
	Hop Land			ρ = -0.15 (0.412)	ρ = -0.03 (0.855)
Balance	Straight Leg			*r* = 0.24 (0.180)	*r* = 0.18 (0.328)
	Bent Leg			ρ = 0.19 (0.289)	ρ = 0.12 (0.492)
	TTS			ρ = 0.03 (0.852)	ρ = -0.14 (0.433)
Force	10 Hops	Max RFD		*r* = 0.23 (0.205)	*r* = 0.25 (0.163)
		Peak Force		*r* = 0.26 (0.149)	*r* = 0.29 (0.105)
		Peak Power		*r* = 0.31 (0.080)	*r* = 0.28 (0.116)
		Peak Velocity		*r* = 0.35 (0.100)†	*r* = 0.38 (0.100)†
Force	IMTP	Max RFD		*r* = 0.19 (0.289)	*r* = 0.07 (0.705)
		Peak Force		*r* = 0.21 (0.251)	*r* = 0.35 (0.100)†
		Impulse 0-100 ms		*r* = -0.15 (0.420)	*r* = -0.09 (0.603)
		Impulse 0-200 ms		ρ = -0.01 (0.951)	ρ = 0.09 (0.633)
		Impulse 0-250 ms		ρ = -0.09 (0.603)	ρ = -0.01 (0.982)
		Impulse 0-300 ms		ρ = -0.14 (0.424)	ρ = -0.08 (0.655)
Isokinetic	Quadriceps	Peak TQ	Concentric	ρ = 0.31 (0.084)	ρ = 0.15 (0.403)
			Eccentric	*r* = 0.09 (0.625)	*r* = -0.09 (0.639)
		Pk TQ/BW	Concentric	*r* = 0.36 (0.100)†	*r* = 0.25 (0.166)
			Eccentric	*r* = 0.15 (0.399)	*r* = -0.07 (0.692)
		Work/BW	Concentric	*r* = 0.38 (0.087)†	*r* = 0.30 (0.095)
			Eccentric	*r* = 0.29 (0.108)	*r* = 0.20 (0.271)
Isokinetic	Hamstring	Peak TQ	Concentric	*r* = 0.21 (0.234)	*r* = 0.17 (0.349)
			Eccentric	ρ = 0.33 (0.059)	ρ = 0.25 (0.168)
		Pk TQ/BW	Concentric	*r* = 0.39 (0.081)†	*r* = 0.31 (0.078)
			Eccentric	*r* = 0.40 (0.069)†	*r* = 0.31 (0.078)
		Work/BW	Concentric	*r* = 0.31 (0.077)	*r* = 0.38 (0.093)†
			Eccentric	ρ = 0.32 (0.068)	ρ = 0.34 (0.051)

(*ρ*) Spearman and (*r*) Pearson correlation coefficients; (†) Bonferroni corrected *p* values; (Peak TQ) Peak torque; (Pk TQ/BW) Peak torque to body weight; (Work/BW) Work to body weight

6.6 Discussion

The aims of this study were to:

1. Investigate the differences between injured and non-injured leg performances across all tests, which include hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic muscle tests.

2. Describe the reference values for the LSI for hop tests and isokinetic muscle tests in ACL reconstructed participants.

3. Investigate the relationship between all of the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks for the injured and non-injured limbs in ACL reconstructed participants.

4. Provide the reference values that are needed for each of the individual tests for both the injured and non-injured limbs in ACL reconstructed participants.

From the results, it can be concluded that there were differences mostly found between the injured and non-injured legs' performance during both the hop and isokinetic strength tests, while the other tests show no differences between both limbs. For the hop tests, for the single-leg hop for distance and crossover hop test, the percentage of participants who achieved 85% of LSI was 72.7%, and 81.8%, respectively. These results are totally different to the recommendations reported by Noyes et al. (1989) who state that a limb symmetry index of 85% or greater was found during different hop tests to be within the normal range for both genders regardless of dominance. As previously mentioned in chapter four in the current thesis, the LSI findings regarding crossover hop test were 100 percent of healthy participants have at least an LSI of 95%, while for single-leg hop for distance test the findings were 100 percent of healthy participants have at least an LSI of 85%. For the single-leg horizontal hop for distance test in ACLR group, the absolute mean difference between the injured and non-injured limbs has been reported by Keays et al. (2003) to be 18.74 cm (155.09 cm for the non-injured and 136.35 cm for the injured) which is similar to what has been found in the current study 17.59% (normalised to leg length) 189.21% for the non-injured and 171.62% for the injured. However, the mean values are higher in the current study than Keays et al. (2003) investigation because the ACLR participants in the current study were highly athletes.

For 2-D FPPA tests, there were no differences found between the injured and non-injured knees' angles during squat and single-leg hop land. These findings are similar to Munro et al. (2012) who examined the differences between the left and right legs using the 2-D analysis of lower limb dynamic valgus in 20 recreationally active university students. Subjects undertook single-leg squat, drop jump, and single-leg landing tests and the authors used the data from tests one and three to investigate the differences between sex and limbs. They found no differences between left and right legs in either sex. However, the study by Munro et al. (2012) was applied to a healthy population, making comparisons almost impossible because of the lack of previous studies examining such differences in an ACL reconstructed participant group.

For balance tests, there were also no differences found between the injured and non-injured legs in overall balance during both static tests (sway area) and dynamic test (TTS). Another study used a different methodology to assess balance (Holm et al., 2004); they found that there were no significant changes in female team handball players for static balance. Additionally, the results from their proprioception device showed that there were no differences between the right and left legs. Although they conducted their study with an athletic population, it is still different from this study, which was conducted with ACL reconstructed athletes. Secondly, they were only female participants not a mixed-gender group same to what has been participated in the current study, and therefore, single-sex study cannot be generalisable to other (mixed-gender) studies.

For force tests, there were no differences found between injured and non-injured leg performance for all variables during 10 consecutive hops, and IMTP tests, apart from one variable during the 10 consecutive hops test, which was that the peak force value was found to have a difference between the injured and non-injured legs' performance. However, such differences have not been evaluated before, making comparison almost impossible because of the lack of any previous studies. Therefore, further investigations are needed in this area to confirm the findings.

Regarding muscle strength symmetry, there were differences found between the injured and non-injured legs' strength performance for the quadriceps and hamstring muscles during the concentric and eccentric muscle actions, including all variables, apart from one variable which was the eccentric hamstring total work to body weight which showed no differences between the limbs. Furthermore, the percentage of the subjects during all muscles strength tests who failed to achieved 85% of the LSI for all the variables ranged from 42.4 % to 60.6 %, and it is usually considered a substantial asymmetry if the difference between limbs is greater than 15 %, and this may put the limbs at increased risk of injury (Knapik et al., 1991). Willigenburg et al. (2014), state that asymmetries between limbs in strength and function could affect athletic performance.

For the injured leg correlation results, as explained in the results section, there was no relationship found between 2-D FPPA (from SLS and single-leg hop land) and both hop performance tests. Although these correlations seem hypothetically to be important to hop performance due to appropriate direction of force application (energy leakage in other planes), no previous study has investigated such a relationship and, therefore, further investigations are needed in this area to confirm the findings. May be the FPPA was not sensitive enough to identify any potential relationships and further research should be conducted using 3-D motion analysis.

For balance correlation tests, there were also no associations found between both balance tests (static and dynamic) and hop performance, and this has been confirmed by Hamilton et al. (2008) who evaluated the relationships between the subject's performance on the THD test and balance tests using the Balance Error Scoring System (BESS), and they concluded that the THD is not associated with the BESS test. Moreover, they evaluated the relationship between the subject's performance in the vertical jump height and balance tests using the

BESS, and concluded that vertical jump height is also not associated with the BESS test. However, the participants were asked to wear shoes for the THD test but not for the BESS, which may have resulted in possible errors in comparing the tests, as different surfaces were used. Secondly, they used THD test which is totally different than to what was used in current study which is crossover hop for distance test as the crossover hop test require changing direction with each hop and crossing over the 15 cm apart lines. Third, they made the comparison between the vertical jump height and balance tests using the BESS, while in the current study horizontal hop tests were compared to balance performance using a portable Kistler force plate. Horizontal hop performance tests are totally different than vertical jump height tests as horizontal hop tests require maintaining the land to achieve complete stabilisation after landing.

Another research study was carried out by Tveter and Holm (2010) to investigate the influence of balance performance on hop distance in a single-leg hop task. This study has reported a weak association between static balance test and hop distance. However, the static balance performance test in their study was done through two 30 second trials on each leg using the KAT 2000, while in the current study it was for 10 seconds from a total of three trials, and their hop distance was tested twice for each leg using the GAITRite system, while in the current study a normal metric tape measure was used to determine the distance of three trials. However, in their study no practice trials were carried out before each of the individual tests and this may invalid the final results because of the learning effect. Furthermore, their study was conducted with a healthy young group, which is totally different to the ACL reconstructed group recruited in the current study. In Phillips and van Deursen’s (2008) study, a strong correlation was found between TTS utilising COP excursion (TTS-COP) and hop distance with ACLD participants. However, Phillips and van Deursen (2008) used ACLD patients, which is also different to the subjects used in the current study (6-9 post-operative ACL reconstructed participants). In addition, in Phillips and van Deursen’s (2008) study the subjects were instructed to hop as far as they could and this is also different than to what has been applied by the participants in the current study as they were instructed to hop 80% from their maximum hop distance achieved during their hop tests. As a result of the lack of published papers on investigating these associations in post-operative ACL reconstructed participants, and due to several balance tests used in the literature along with different methodologies, the final conclusion on the relationship between hop distance tests and balance performance is still difficult to provide and it requires further investigation.

For force production during the 10 consecutive hops test and IMTP, there were several positive correlations found between the variables of the 10 consecutive hops test and both hop distance tests. However, the IMTP test failed to show any associations with both hop performance tests. Although no previous studies have investigated the same correlations between both force tests (10 consecutive hops and IMTP) and hop performance, some studies have evaluated quite similar correlations, but with vertical hop performance. Myer et al. (2012) undertook a study of thirty-three unilateral ACLR athletes, 10 males and 23 females, who were assessed by a physician to be able to return to their sports after ACL surgery and rehabilitation. They performed the single-legged vertical hop test continuously for 10 seconds on a force plate. Maximum VGRF was recorded during each single limb landing. This study concluded that deficits in unilateral force development during vertical hop height and absorption in normalised VGRF persist in an athletes' single-leg performance after ACL surgery and full return to sports. These symmetry deficits seem to be independent of time after ACL reconstruction. Although Myer et al. (2012) used a same sample size exactly the same as that used in the current study (33 ACLR participants), different parameters and variables were tested in their study, which may have caused variations. Moreover, the participants in Myer et al. (2012) study were instructed to swing their arms when they hop and this may affect the resultant final force data because there was an excessive force that might be produced from swinging the arms (Harman et al. 1990), and therefore, keeping the hands on the hips during jumping activities reduces the effect of arm motion to better reflect lower limb performance (Impellizzeri et al., 2007).

Another study by Angelozzi et al. (2012) aimed to investigate the RFD to 30% (RFD_{30}), 50% (RFD_{50}), and 90% (RFD_{90}) of maximal voluntary isometric contraction (MVIC) as an additional outcome measure to determine readiness to return to sport after ACL reconstruction. Forty-five professional male football players who underwent an ACL surgery were recruited. MVIC, RFD_{30}, RFD_{50}, and RFD_{90} testing was done pre-injury, as part of a standard pre-season evaluation, and at six months and 12 months post-ACL reconstruction. The results of this study suggest that RFD criteria may be a useful adjunct outcome measure for the decision to return to sports following ACL reconstruction, as they found that there were significant deficits in RFD at six months post-ACL reconstruction. West et al. (2011) investigated force generation in thirty-nine professional rugby league players. After forty-eight hours of trial familiarisation, the participants applied a maximal IMTP with approximately 120-130° bend at the knee, and CMJ. They found that peak RFD, peak force, and F100ms values during IMTP were moderately correlated to dynamic performance (CMJ height). The results of West et al. (2011) are different to the findings in the current study (no associations found between IMTP and both hop performances), and the reasons behind these differences are because West et al. (2011) used a highly athletic population with different tasks performed in their study, including CMJ height and this is different than the horizontal hop land performance as horizontal hop activity require controlling the land to achieve balance after landing.

Another study by Khamoui et al. (2011) investigated the association between the isometric force-time characteristics during IMTP and vertical jump height in nineteen recreationally trained men; isometric force-time characteristics include RFD at various time frames (IsoRFD50, 100, 150, 200, and 250 milliseconds). They found no associations between RFD at all various time frames (IsoRFD50, 100, 150, 200, and 250 milliseconds) and vertical jump height performance, and this was similar to what has been found in the current study for both hop test correlations, which were no correlations found between impulses at all various time frames (impulse 0-100, 200, 250, and 300 ms), and both hop tests (single-leg hop for distance and crossover hop), apart from the different methodologies and subjects used by Khamoui et al. (2011) and in the current study. Although in Khamoui et al. (2011) study the tasks performed were bilateral (more controlled than unilateral) which is different than to what were used in the current study (unilateral), they found similar results, and this could provide an evidence that using bilateral hop testing may not differ than unilateral to investigate overall lower limb performance. Another study by Mcguigan et al. (2010) aimed to determine the relationships between measures of the IMTP force characteristics and vertical jump performance (height) in recreationally trained men. The results indicate that there were no correlations found between maximum RFD values and vertical jump height, and this was similar to what has been found in the current study- no correlations noted between maximum RFD value during IMTP and both hop tests, apart from the different methodologies and subjects also used by Mcguigan et al. (2010) and in the current study. As a result of the shortage in the published papers of studies investigating these associations in post-operative ACLR participants, and due to several force tests used in the literature involving different methodologies, the final conclusion on the relationship between horizontal hop distance tests and force production performance is still difficult to provide and requires further investigation.

For isokinetic muscle tests, there were moderate to strong correlations found between both quadriceps and hamstring strength variables (peak torque, peak torque to body weight, and total work to body weight values) and hop performance in ACLR participants, apart from hamstring total work to body weight values in both concentric and eccentric muscle actions not being associated with hop performance. A strong correlation was found by Petschnig et al. (1998) who investigated the association between quadriceps concentric peak torque value and single-leg hop for distance in ACLR patients nearly one year post-surgery ($r = 0.51$), and this is quite similar to the current study’s findings (ρ = 0.55). Wilk et al. (1994) also noted a correlation between isokinetic muscle testing and three single-leg hop tests in ACLR patients. The participants performed isokinetic strength testing on a Biodex dynamometer at three speeds, 180, 300 and 450 degrees/sec., for the quadriceps and hamstring muscles. In addition, one-legged functional tests were examined as timed hops, hops for distance and crossover triple hops. It was concluded that a positive relationship exists between quadriceps muscle variables at speeds of 180 and 300 degrees/sec. and the three hop tests. However, the authors used very high speeds when testing muscles strength using Biodex system (180, 300 and 450 degrees/sec), and the limitation with using such speeds is that there might be a missing force (from resisting against the Biodex attachment) because of the fast movement of the dynamometer. A slightly similar association has also been found in the study by Noyes et al. (1991), which reports positive relationships between muscle strength measures and hop tests in sixty-seven participants. They have reported moderate correlations between both hamstring and quadriceps muscle strength variables and single-leg hop tests. However, Noyes et al. (1991) performed the tests with ACL deficit patients, which is different to the group in this study (ACLR participants). Therefore, and from the previous discussion regarding isokinetic muscle testing it can be concluded that knee muscles strength is a critical factor to hop performance for ACLR population. Clinicians need to concentrate on strengthening knee muscles (quadriceps and hamstring) after ACL injury/ reconstruction.

For the non-injured leg correlation results, as explained in the results, there were no correlations found between all the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks. The reason behind having no associations in the non-injured limb may be as a result of concentrating on rehabilitating the injured limb and ignoring the non-injured limb, and this situation is confirmed by Chung et al. (2015) who state that once an ACL injury has occurred, it will negatively affect contralateral limb performance. Chung et al. (2015) have demonstrated that after ACL injury, knee extensor muscle strength and the functional status of the non-injured limb were reduced, even at two years after ACL surgery. However, hamstring muscle strength was restored to normal levels. They conclude that not only the ACL-reconstructed knee should be taken care of to restore its strength and functional status, but also the contralateral limb.

One possible limitation is that regression analysis was not performed in this chapter, however as all variables were linked to force production (e.g. force is highly correlated with RFD and power) it was not considered necessary as each of these force-time variables is inextricably linked.

6.7 Conclusion

This study has aimed to investigate the differences between injured and non-injured leg performances across all tests, which include hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic muscle tests, and to describe the reference values for the LSI for hop tests and isokinetic muscle tests in ACL reconstructed participants. Furthermore, it has investigated the relationship between all of the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance for the injured and non-injured limbs during single-leg hop for distance and crossover hop tasks in ACL reconstructed participants, and provided the reference values that are needed for each of the individual tests for both the injured and non-injured limbs. Therefore, from the study, it can be concluded that:

- Differences have been found between the injured and non-injured legs' performances throughout hop tests and isokinetic muscle strength tests, while the rest of the tests revealed no differences between the limbs.
- Symmetry between limbs did not exist in both tests, which were hop tests and isokinetic muscle tests, from which it can be concluded that one leg's performance cannot define the other.
- Dynamic force generation test (10 consecutive hops) and both quadriceps and hamstring muscle strength during both concentric and eccentric muscle actions seem to be the most predictable tests for hop performances (both single-leg hop for distance and crossover hop) for the injured limb.
- There were no correlations found for the non-injured limbs between all the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks, and the implications of this result are that this limb (the non-injured limb) might have a high risk of injury for any ACLR participants if the limb is not given sufficient rehabilitation.
- The existing return to play criteria appears to be insufficient based on the fact that asymmetries between limbs and deficits in both limbs excited in the participants in this study.

All the ACLR participants participating in the study have been medically released to return to sport. The findings of this chapter illustrate the need for appropriate quantitative tests to be undertaken to define status prior to return to sport, as a significant number of subjects failed to come close to recognised standards for LSI. The study also highlights that strength deficits could impact on functional performance (hop tests), similar to healthy subjects in the previous chapter. The findings in this chapter also highlight that the uninjured leg does not perform in a manner which could be regarded as normal and care may need to be exercised in comparing the ACLR limb to this leg and therefore maintenance of strength and functional performance during the rehabilitation of the injured leg is essential.

Chapter (7)

Summary, Conclusion and Recommendations for Future Work

7 Chapter 7: Summary, Conclusions and Recommendations for Future Work

7.1 Summary

Hopping is a common task performed in many sports. Physical performance and athletic function can be measured using hop tests. Such tests are useful for monitoring progress and to decide whether the person is ready to return to sport or everyday activities following an injury or surgery. Moreover, landing from a hop involves large forces being applied by the knee and hip extensors and ankle plantar-flexors to control joint flexion and decelerate the body (Mcnitt-Gray, 1993). When landing, the lower extremities help to absorb and dissipate the GRF resulting from each hop. In studies of landing, there has been concentration on the biomechanical implications of impact and of the total load on lower limb tissues (Devita and Skelly, 1992). However, during different activities, the landing phase may be overlooked, which may contribute towards poor performance or injury. Thus, there has been an increased focus on the factors that contribute to different hop and landing techniques (Dufek and Bates, 1991), especially in ACL reconstructed participants. Many studies have confirmed that hop tests are able to reflect functional limitations in the lower extremities; however, the ability of hop tests to discover specific deficiencies remains unclear (Barber et al., 1990; Noyes et al., 1991).

One of the factors which have been linked to hop performance is balance. In ACL injuries, it has been hypothesised as being attributable to frequent landing from a hop that requires the subject to maintain their balance on landing (Griffin et al., 2000). Balance testing is an important component in sports outcome measurements, but especially in the sports rehabilitation process, particularly where landing or maintaining balance is a key component of the activity. Another contributing factor to hop performance is lower limb strength, as higher levels of lower limb strength will potentially result in improved performance (Myer et al., 2006), more controlled landings and a reduction in injuries (Jacobs et al., 2007). In addition, it has been found that there is an association between concentric strength and hop distance (Hamilton et al., 2008). Landing requires large eccentric muscle forces to be exerted by the knee, hip and ankle extensor muscles during the landing phase, when joints are moving into a flexed position, in order to decelerate the body (McNitt-Gray, 1993). Therefore, one of the most important indicators of athletic ability would appear to be muscle strength, and this is particularly important for sports involving a high generation of force over a short time (Newton and Kraemer, 1994), and rapid decelerations and change of direction. From this point, another contributing factor that has been linked to hop performance is force generation. Different force generation tests have been undertaken previously, however, the majority of these tests have been correlated with vertical jump performance and not with horizontal hop distances. Some of these studies were dynamic (i.e SJ and CMJ), and some others were static (IMTP). A good example of this is West et al. (2011) who found that PF and peak RFD during IMTP are correlated with CMJ height, and there are other examples, as previously explained in the literature review. Additionally, it is important to consider landing from hop tasks with relatively neutral lower limb biomechanics, as it has been demonstrated that most ACL injuries, around 80%, are non-contact (Renstrom et al., 2008), for example, as a result of landing poorly from a high hop or deceleration during sport. For this reason, many screening tests have been described in the literature for evaluating dynamic knee valgus (Munro et al., 2012). These tests have involved the SLS (Willson and Davis, 2008), drop vertical jump (Herrington and Munro, 2010), single-leg landing (Lawrence et al., 2008), and drop landing (Decker et al., 2003).

From what has been explained above, it shows that hop tests could be important and should be undertaken with extra care during rehabilitation programmes to measure performance. Although several studies have examined the relationship between lower extremity balance, TTS, muscle strength, force generation, and 2-D knee kinematics after hopping as single tasks, no study has ever examined the relationship between all of these factors and hop performance in both healthy and six to nine months post-op ACL reconstructed participant groups. In addition, no study has provided values for each of the individual tests for both groups, or defined the level of hop distance reference values for both groups. As a result of the different methods and parameters used in the aforementioned studies, such as variability in testing duration, testing tools, and populations, this situation may require further investigation. Therefore, given this gap in the literature, there would appear to be justification for conducting this study to investigate the relationship between all of these factors and hop performance in both healthy and six to nine months ACL reconstructed participant groups.

The aims of this thesis were to:

The overall aim of the work contained within this thesis is to have a better understanding of hop test performance and the factors which influence it. In order to answer this question, the work undertaken has been broken down into a number of elements with specific aims:

1. Investigate the reliability of the individual tests which consist of hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic strength testing to establish the measurement error of these.

2. Investigate the reference values for each of the individual test procedures, as well as if limb symmetry exists for hop tests and isokinetic muscle strength tests. Attempt to establish

reference performance ranges for the tests so sub-optimal performance can be identified in either group in a future study or what normal limb symmetry indexes for both tests (hop tests and isokinetic muscle strength tests) are.

3. Investigate the relationship between all of the tests and hopping performance in a healthy population.

4. Investigate the relationship between all of the tests and hopping performance in participants six to nine months post ACL reconstruction.

7.2 Conclusion

Regarding the first aim, which was to examine the within- and between-days reliability of five tests (hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic muscle tests), and establish standard measurement error (%SEM) during these tasks in recreational healthy participants, this study has found that the majority of the ICC values for all tests were excellent across all variables during within- and between-day sessions testing, showing these tests to be reliable. However, impulses from 0 - 100, 200, 250, 300 ms had less reliable variables across all IMTP results, with ICC ranging from 0.49 to 0.91, and the possible explanation for this decline is that the participants might not have pulled the bar hard and fast enough consistently during the IMTP test. It is seems to be that the participants sometimes pulled hard but not very fast and vice versa.

The second aim of this study was to investigate the differences between right and left leg performances across all tests (hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic muscle tests), and to describe reference values for the LSI for hop tests and isokinetic muscle strength tests for 20 recreationally healthy participants. However, the main reason behind conducting this study was to identify whether one leg’s performance can define the other, and further to this investigation, if the limbs were found to be symmetrical across all the tests, then the next study which was the main correlation in healthy participants would be carried out using the right leg only. This study has concluded that no differences were found between right and left leg performance during all the tests. In addition, symmetry between limbs exists for both hop tests (100% of participants with ≥ 85% LSI), while symmetry between limbs almost exists for muscle strength tests, from which it can be concluded that one leg’s hop performance can define the other.

The third aim of this study was to investigate the relationship between all of the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks in 65 healthy participants. This would then also provide the reference values that are needed for each of the individual tests. The conclusion of this element of the study is that several positive correlations were found between force generation tests and hop performance (single-leg hop for distance and crossover hop). Positive correlations were found between quadriceps muscle total work to body weight during concentric muscle contraction and hop performance tests. The same positive correlations were found between ankle plantar flexors peak torque to body weight, and total work to body weight values during concentric and eccentric muscle actions and hop performance tests, whilst other tests failed to show any association with hop performance. The relationships also appeared stronger when undertaking multiple hops (i.e. crossover hop test) then a single hop, which may be related to the greater plyometric (muscle stretch-shorten) action.

Finally, the last aim of the current study was to investigate the differences between injured and non-injured leg performances across all tests (hop tests, 2-D FPPA, balance tests, force generation tests, and isokinetic muscle tests), and describe reference values for the LSI for hop tests and isokinetic muscle tests in ACL reconstructed participants. Also, to investigate the relationship between all of the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks for the injured and non-injured limbs in ACL reconstructed participants, and provide the reference values that are needed for each of the individual tests for both the injured and non-injured limbs. This study has found that there were differences between injured and non-injured leg performance throughout the hop tests and isokinetic muscle strength tests, while the rest of the tests found no differences between the limbs. Additionally, symmetry between limbs did not exist across both tests (which were hop tests and isokinetic muscle tests), from which it can be concluded that one leg’s performance cannot define the other. With regard to the correlations findings, dynamic force generation test (10 consecutive hops) and both quadriceps and hamstring muscle strength during both concentric and eccentric muscle actions seems to be the most predictable tests for both hop performances (single-leg hop for distance and crossover hop) for the injured limb. However, there were no correlations found for the non-injured limbs between all the tests (2-D FPPA, balance, force generation, and isokinetic muscle strength tests) and hop performance during single-leg hop for distance and crossover hop tasks, and the implications of this result is that this limb (the non-injured) might have a higher risk of injury for ACL reconstructed participants if this limb (the non-injured) does not have sufficient rehabilitation following the injury. The existing return to play criteria appears to be insufficient based on the fact that asymmetries between limbs and deficits in both limbs excited in the participants in this study.

All the ACLR participants participating in the current study have been medically released to return to sport. The findings of this study illustrate the need for appropriate quantitative tests to be undertaken to define status prior to return to sport, as a significant number of subjects failed to come close to recognised standards for LSI for strength and hop performance, for example. The study also highlights that strength deficits could impact on functional performance (hop tests), similar to healthy subjects in chapter five. The findings of this study also highlight that the uninjured leg does not perform in a manner which could be regarded as normal because it was assumed to show the same correlations which have been found in healthy participants study in chapter five (relationships of force generation and muscle strength to hop performance), but it failed to show any association to hop performance, and care may need to be exercised in comparing the ACLR limb to this leg and therefore maintenance of strength and functional performance during the rehabilitation of the injured leg is essential. Further research should consider period assessment of the non-injured limb to determine its performance during rehabilitation of the injured limb to identify any changes in performance occurred.

As force generation and muscle strength of lower limbs seem to be the most contributing factors to hop performance in healthy and ACLR participants, hop tests can be used in a clinic to indicate potential deficits in strength or force generation in lower limbs in both populations. In addition, to determine the readiness to return to play hop tests should be included in the rehabilitation programs to investigate the achieved distances after injuries are they within the reference values or not, also to evaluate the progress of hop performance in their final stages of rehabilitation especially after strengthening exercises.

7.3 Recommendations for Future Work

Based on the results of this thesis and the subsequent discussion, several questions have been raised with regard to future research. Primarily, from the reliability study, it is recommended that hop, 2-D FPPA, balance, force generation, and isokinetic muscle strength tests should be used in future studies. Moreover, further research involving different athletic populations, including a range of different sporting activities, would be useful in order to explore whether average hopping performance differs between sports. This would help to identify those athletes who are considered as having poor hopping performance, which leaves them at higher risk of injuries.

The positive findings regarding hop correlations in ACLR participants presented in Chapter Six require a much greater number of participants to be recruited in the future, adding to that ACLR participants (recreationally active) would also allow a clear comparison of the findings to ACLR athletes. Furthermore, ankle plantar flexor muscles in ACLR participants should be tested to investigate if a correlation can be found between hop performance and ankle plantar flexor muscles strength as the such correlations that were demonstrated by healthy participants in the study, as described in Chapter Five, which found that there were positive correlations between ankle plantar flexors peak torque to body weight and total work to body weight values during concentric and eccentric muscle actions and hop performance tests; therefore, this has been considered a limitation in the current study. However, the first reason behind excluding this test was because this test took a long time for healthy participants to complete during their examinations, and therefore, to avoid any fatigue that might occur to ACLR participants during their evaluations, this test was excluded. The second reason was the limited time for ACLR participants to participate in the current study (maximum of two hours), and so this test was taken out. However, the decision to keep the quadriceps and hamstring muscles and exclude the hip extensor and ankle plantar flexor muscles in ACLR participants study was made before having the final results on healthy correlations (see Chapter Five) because the data collection for both correlation studies of healthy and ACLR participants were undertaken during almost the same period of time. Therefore, the main reason behind choosing quadriceps and hamstring muscles was because it has been reported in previous studies that only knee muscles, quadriceps and hamstrings, are correlated with hop performance and taken into considerations with ACLR participants (Keays et al., 2003; Petschnig et al., 1998; Wilk et al., 1994; Noyes et al., 1991); therefore, these two muscles were chosen to be tested with the ACLR participants.

It has been demonstrated that the non-injured limb shows no association to hop performance tests for ACLR participants in the correlation study (Chapter Six), therefore an intervention study should be undertaken for the contralateral limb in ACLR participants, to investigate whether rehabilitating the contralateral limb in the same way as the injured limb would make any changes to contralateral limb performance, as this should reduce the risk of injuries occurring to the non-injured limb as well.

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Appendix (A)

Appendix (A1)

University of Salford
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Research, Innovation and Academic Engagement Ethical Approval Panel

College of Health & Social Care
AD 101 Allerton Building
University of Salford
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T +44(0)161 295 7016
r.shuttleworth@salford.ac.uk

www.salford.ac.uk/

6 November 2013

Dear Hussain,

RE: ETHICS APPLICATION HSCR13/51 – **Factors which influence the performance of hop tests. Study 1: Reliability and relationship between squat jump, countermovement jump, ten jumps and isometric jump tests**

Based on the information you provided, I am pleased to inform you that application HSCR13/51 has now been approved, on condition that you add the images to the participant information sheet, and that you also include what will happen to a person's data if they withdraw. This is on the consent form but not on the participant information sheet.

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 (A2)

University of
Salford
MANCHESTER

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University of Salford
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6 November 2013

Dear Hussain,

RE: ETHICS APPLICATION HSCR13/57 – Factors which influence the performance of hop tests. Study 2: Reliability of isokinetic test of hip extensions, knee extensors and flexors and ankle plantar flexor muscles during both eccentric and concentric muscle actions.

Based on the information you provided, I am pleased to inform you that application HSCR13/57 has now been approved, on condition that you add the images to the participant information sheet, and that you also include what will happen to a person's data if they withdraw. This is on the consent form but not on the participant information sheet.

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 (A3)

University of Salford
MANCHESTER

Research, Innovation and Academic Engagement Ethical Approval Panel

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6 November 2013

Dear Hussain,

RE: ETHICS APPLICATION HSCR13/58 – Factors which influence the performance of hop tests. Study 3: Reliability and relationship between straight leg balance test, bent leg balance test and horizontal hop balance test

Based on the information you provided, I am pleased to inform you that application HSCR13/58 has now been approved, on condition that you add the images to the participant information sheet, and that you also include what will happen to a person's data if they withdraw. This is on the consent form but not on the participant information sheet.

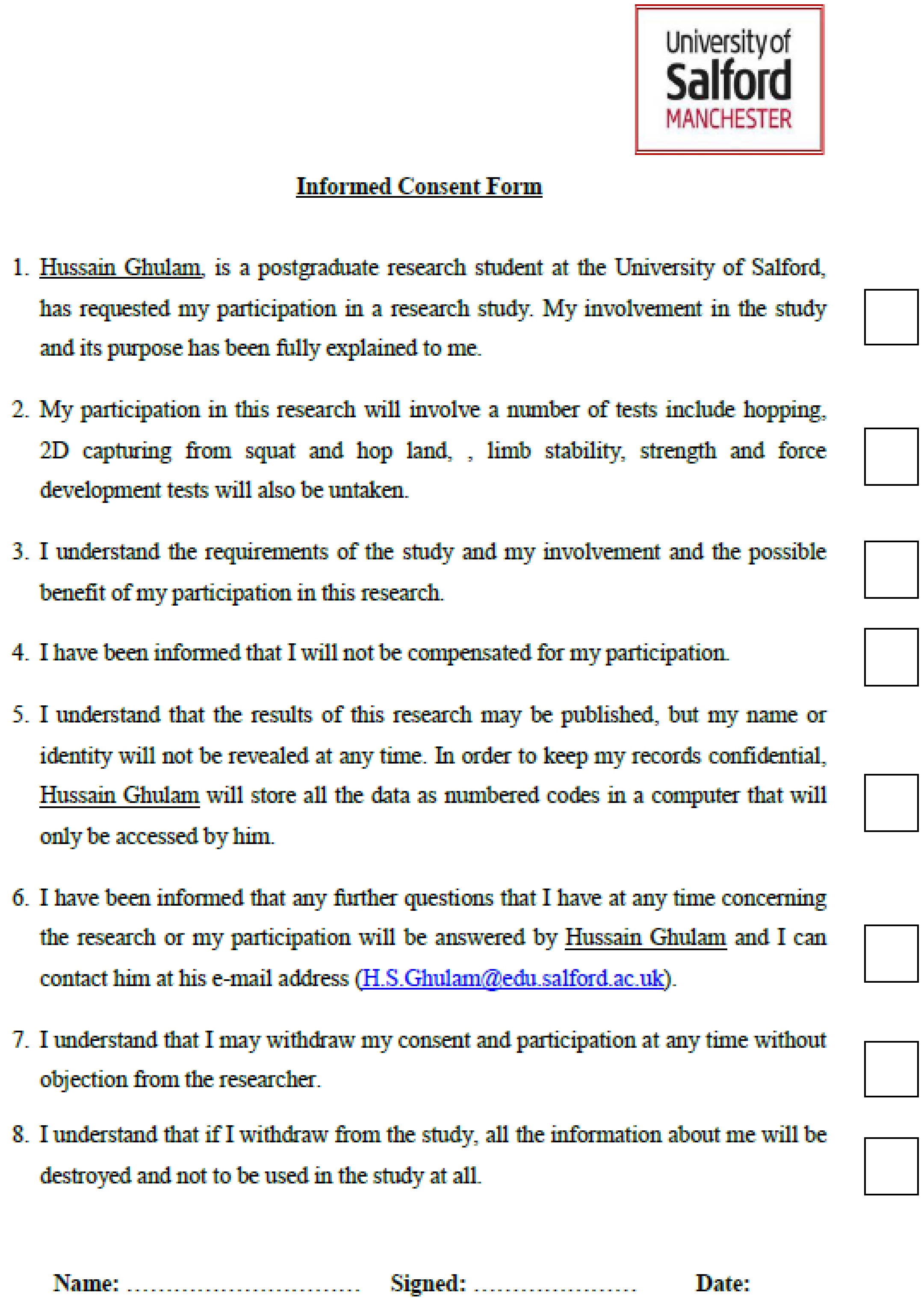
If there are any changes to the project and/ or its methodology, please inform the Panel as soon as possible.

Yours sincerely,

Rachel Shuttleworth

Rachel Shuttleworth
College Support Officer (R&I)

Appendix (A4)



Informed Consent Form

1. Hussain Ghulam, 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. ☐
2. My participation in this research will involve a number of tests include hopping, 2D capturing from squat and hop land, , limb stability, strength and force development tests will also be untaken. ☐
3. I understand the requirements of the study and my involvement and the possible benefit of my participation in this research. ☐
4. I have been informed that I will not be compensated for my participation. ☐
5. I understand that the results of this research may be published, but my name or identity will not be revealed at any time. In order to keep my records confidential, Hussain Ghulam will store all the data as numbered codes in a computer that will only be accessed by him. ☐
6. I have been informed that any further questions that I have at any time concerning the research or my participation will be answered by Hussain Ghulam and I can contact him at his e-mail address (H.S.Ghulam@edu.salford.ac.uk). ☐
7. I understand that I may withdraw my consent and participation at any time without objection from the researcher. ☐
8. I understand that if I withdraw from the study, all the information about me will be destroyed and not to be used in the study at all. ☐

Name: .... **Signed:** .... **Date:**

Appendix (B)

Appendix (B)

Tests of Normality for the Reliability Study

Test		Shapiro-Wilk		
		Statistic	df	Sig.
Hop	Rt Single-leg horizontal hop for distance 1st session	.951	12	.657
	Rt Single-leg horizontal hop for distance 2nd session	.926	12	.337
	Rt Single-leg horizontal hop for distance 3rd session	.916	12	.254
	Lt Single-leg horizontal hop for distance 1st session	.944	12	.552
	Lt Single-leg horizontal hop for distance 2nd session	.928	12	.357
	Lt Single-leg horizontal hop for distance 3rd session	.968	12	.884
	Rt Crossover hop for distance 1st session	.851	12	.038
	Rt Crossover hop for distance 2nd session	.867	12	.061
	Rt Crossover hop for distance 3rd session	.865	12	.057
	Lt Crossover hop for distance 1st session	.839	12	.027
	Lt Crossover hop for distance 2nd session	.852	12	.039
	Lt Crossover hop for distance 3rd session	.871	12	.067
2-D	Rt FPPA squat 1st session	.972	12	.935
	Rt FPPA squat 2nd session	.936	12	.446
	Rt FPPA squat 3rd session	.912	12	.228
	Lt FPPA squat 1st session	.942	12	.520
	Lt FPPA squat 2nd session	.950	12	.631
	Lt FPPA squat 3rd session	.948	12	.614
	Rt FPPA hop land 1st session	.924	12	.321
	Rt FPPA hop land 2nd session	.906	12	.187
	Rt FPPA hop land 3rd session	.879	12	.085
	Lt FPPA hop land 1st session	.940	12	.504
	Lt FPPA hop land 2nd session	.853	12	.039
	Lt FPPA hop land 3rd session	.865	12	.057
Balance	Rt straight leg balance 1st session	.931	12	.395
	Rt straight leg balance 2nd session	.847	12	.034
	Rt straight leg balance 3rd session	.938	12	.469
	Lt straight leg balance 1st session	.935	12	.433
	Lt straight leg balance 2nd session	.913	12	.231
	Lt straight leg balance 3rd session	.945	12	.567
	Rt bent leg balance 1st session	.925	12	.328
	Rt bent leg balance 2nd session	.920	12	.289
	Rt bent leg balance 3rd session	.900	12	.161
	Lt bent leg balance 1st session	.943	12	.538
	Lt bent leg balance 2nd session	.939	12	.484
	Lt bent leg balance 3rd session	.952	12	.672
	Rt leg TTS 1st session	.921	12	.291
	Rt leg TTS 2nd session	.924	12	.317
	Rt leg TTS 3rd session	.912	12	.224
	Lt leg TTS 1st session	.893	12	.128
	Lt leg TTS 2nd session	.925	12	.334
	Lt leg TTS 3rd session	.929	12	.365

Force (Squat Hop)	Rt Max RFD 1st session	.969	12	.898
	Rt Max RFD 2nd session	.942	12	.531
	Rt Max RFD 3rd session	.949	12	.622
	Lt Max RFD 1st session	.930	12	.377
	Lt Max RFD 2nd session	.906	12	.191
	Lt Max RFD 3rd session	.916	12	.258
	Rt Peak force 1st session	.889	12	.116
	Rt Peak force 2nd session	.937	12	.463
	Rt Peak force 3rd session	.938	12	.472
	Lt Peak force 1st session	.905	12	.185
	Lt Peak force 2nd session	.892	12	.126
	Lt Peak force 3rd session	.869	12	.063
	Rt Peak power 1st session	.941	12	.515
	Rt Peak power 2nd session	.946	12	.576
	Rt Peak power 3rd session	.959	12	.772
	Lt Peak power 1st session	.904	12	.179
	Lt Peak power 2nd session	.874	12	.073
	Lt Peak power 3rd session	.878	12	.083
	Rt Peak velocity 1st session	.904	12	.178
	Rt Peak velocity 2nd session	.953	12	.678
	Rt Peak velocity 3rd session	.931	12	.388
	Lt Peak velocity 1st session	.939	12	.481
	Lt Peak velocity 2nd session	.939	12	.480
	Lt Peak velocity 3rd session	.925	12	.329
Force (Countermovement Hop)	Rt Max RFD 1st session	.941	12	.515
	Rt Max RFD 2nd session	.943	12	.539
	Rt Max RFD 3rd session	.942	12	.530
	Lt Max RFD 1st session	.932	12	.397
	Lt Max RFD 2nd session	.927	12	.345
	Lt Max RFD 3rd session	.911	12	.217
	Rt Peak force 1st session	.978	12	.972
	Rt Peak force 2nd session	.985	12	.997
	Rt Peak force 3rd session	.983	12	.994
	Lt Peak force 1st session	.950	12	.642
	Lt Peak force 2nd session	.925	12	.333
	Lt Peak force 3rd session	.940	12	.498
	Rt Peak power 1st session	.949	12	.621
	Rt Peak power 2nd session	.933	12	.409
	Rt Peak power 3rd session	.927	12	.354
	Lt Peak power 1st session	.930	12	.383
	Lt Peak power 2nd session	.948	12	.613
	Lt Peak power 3rd session	.951	12	.650
	Rt Peak velocity 1st session	.924	12	.316
	Rt Peak velocity 2nd session	.916	12	.252
	Rt Peak velocity 3rd session	.895	12	.135
	Lt Peak velocity 1st session	.919	12	.277
	Lt Peak velocity 2nd session	.891	12	.122
	Lt Peak velocity 3rd session	.924	12	.323

Force (10 Hops)	Rt Max RFD 1st session	.921	12	.291
	Rt Max RFD 2nd session	.938	12	.475
	Rt Max RFD 3rd session	.915	12	.248
	Lt Max RFD 1st session	.956	12	.727
	Lt Max RFD 2nd session	.968	12	.889
	Lt Max RFD 3rd session	.967	12	.881
	Rt Peak force 1st session	.971	12	.923
	Rt Peak force 2nd session	.971	12	.924
	Rt Peak force 3rd session	.966	12	.867
	Lt Peak force 1st session	.947	12	.597
	Lt Peak force 2nd session	.929	12	.371
	Lt Peak force 3rd session	.967	12	.877
	Rt Peak power 1st session	.943	12	.533
	Rt Peak power 2nd session	.947	12	.591
	Rt Peak power 3rd session	.957	12	.735
	Lt Peak power 1st session	.966	12	.860
	Lt Peak power 2nd session	.984	12	.994
	Lt Peak power 3rd session	.965	12	.852
	Rt Peak velocity 1st session	.928	12	.361
	Rt Peak velocity 2nd session	.897	12	.147
	Rt Peak velocity 3rd session	.953	12	.686
	Lt Peak velocity 1st session	.982	12	.989
	Lt Peak velocity 2nd session	.981	12	.986
	Lt Peak velocity 3rd session	.971	12	.922
IMTP	Rt Max RFD 1st session	.896	12	.140
	Rt Max RFD 2nd session	.904	12	.177
	Rt Max RFD 3rd session	.893	12	.129
	Lt Max RFD 1st session	.935	12	.434
	Lt Max RFD 2nd session	.867	12	.061
	Lt Max RFD 3rd session	.858	12	.046
	Rt Peak force 1st session	.919	12	.278
	Rt Peak force 2nd session	.915	12	.251
	Rt Peak force 3rd session	.905	12	.187
	Lt Peak force 1st session	.972	12	.929
	Lt Peak force 2nd session	.977	12	.968
	Lt Peak force 3rd session	.982	12	.992
	Rt Impulse 0-100 ms 1st session	.978	12	.974
	Rt Impulse 0-100 ms 2nd session	.748	12	.003
	Rt Impulse 0-100 ms 3rd session	.761	12	.003
	Lt Impulse 0-100 ms 1st session	.643	12	.000
	Lt Impulse 0-100 ms 2nd session	.931	12	.390
	Lt Impulse 0-100 ms 3rd session	.847	12	.034
	Rt Impulse 0-200 ms 1st session	.947	12	.590
	Rt Impulse 0-200 ms 2nd session	.754	12	.003
	Rt Impulse 0-200 ms 3rd session	.788	12	.007
	Lt Impulse 0-200 ms 1st session	.751	12	.003
	Lt Impulse 0-200 ms 2nd session	.962	12	.814
	Lt Impulse 0-200 ms 3rd session	.867	12	.061

	Rt Impulse 0-250 ms 1st session	.940	12	.503
	Rt Impulse 0-250 ms 2nd session	.956	12	.729
	Rt Impulse 0-250 ms 3rd session	.948	12	.601
	Lt Impulse 0-250 ms 1st session	.789	12	.007
	Lt Impulse 0-250 ms 2nd session	.947	12	.594
	Lt Impulse 0-250 ms 3rd session	.945	12	.571
	Rt Impulse 0-300 ms 1st session	.966	12	.869
	Rt Impulse 0-300 ms 2nd session	.937	12	.463
	Rt Impulse 0-300 ms 3rd session	.965	12	.855
	Lt Impulse 0-300 ms 1st session	.825	12	.018
	Lt Impulse 0-300 ms 2nd session	.957	12	.747
	Lt Impulse 0-300 ms 3rd session	.918	12	.269
Isokinetic Quadriceps	Rt Peak torque (Concentric) 1st session	.808	12	.012
	Rt Peak torque (Concentric) 2nd session	.799	12	.009
	Rt Peak torque (Concentric) 3rd session	.814	12	.014
	Lt Peak torque (Concentric) 1st session	.891	12	.121
	Lt Peak torque (Concentric) 2nd session	.875	12	.076
	Lt Peak torque (Concentric) 3rd session	.881	12	.090
	Rt Peak torque (Eccentric) 1st session	.896	12	.142
	Rt Peak torque (Eccentric) 2nd session	.884	12	.098
	Rt Peak torque (Eccentric) 3rd session	.914	12	.243
	Lt Peak torque (Eccentric) 1st session	.899	12	.155
	Lt Peak torque (Eccentric) 2nd session	.927	12	.351
	Lt Peak torque (Eccentric) 3rd session	.909	12	.207
	Rt Peak torque/BW (Concentric) 1st session	.783	12	.006
	Rt Peak torque/BW (Concentric) 2nd session	.773	12	.005
	Rt Peak torque/BW (Concentric) 3rd session	.788	12	.007
	Lt Peak torque/BW (Concentric) 1st session	.856	12	.044
	Lt Peak torque/BW (Concentric) 2nd session	.871	12	.067
	Lt Peak torque/BW (Concentric) 3rd session	.900	12	.161
	Rt Peak torque/BW (Eccentric) 1st session	.864	12	.055
	Rt Peak torque/BW (Eccentric) 2nd session	.894	12	.131
	Rt Peak torque/BW (Eccentric) 3rd session	.865	12	.057
	Lt Peak torque/BW (Eccentric) 1st session	.900	12	.161
	Lt Peak torque/BW (Eccentric) 2nd session	.871	12	.068
	Lt Peak torque/BW (Eccentric) 3rd session	.902	12	.169
	Rt Work/BW (Concentric) 1st session	.958	12	.749
	Rt Work/BW (Concentric) 2nd session	.941	12	.517
	Rt Work/BW (Concentric) 3rd session	.953	12	.683
	Lt Work/BW (Concentric) 1st session	.967	12	.876
	Lt Work/BW (Concentric) 2nd session	.948	12	.614
	Lt Work/BW (Concentric) 3rd session	.943	12	.541
	Rt Work/BW (Eccentric) 1st session	.915	12	.244
	Rt Work/BW (Eccentric) 2nd session	.911	12	.217
	Rt Work/BW (Eccentric) 3rd session	.915	12	.246
	Lt Work/BW (Eccentric) 1st session	.913	12	.230
	Lt Work/BW (Eccentric) 2nd session	.918	12	.269
	Lt Work/BW (Eccentric) 3rd session	.935	12	.441

Isokinetic Hamstring	Rt Peak torque (Concentric) 1st session	.950	12	.644
	Rt Peak torque (Concentric) 2nd session	.936	12	.445
	Rt Peak torque (Concentric) 3rd session	.976	12	.961
	Lt Peak torque (Concentric) 1st session	.887	12	.109
	Lt Peak torque (Concentric) 2nd session	.922	12	.304
	Lt Peak torque (Concentric) 3rd session	.946	12	.575
	Rt Peak torque (Eccentric) 1st session	.950	12	.641
	Rt Peak torque (Eccentric) 2nd session	.969	12	.901
	Rt Peak torque (Eccentric) 3rd session	.940	12	.495
	Lt Peak torque (Eccentric) 1st session	.948	12	.609
	Lt Peak torque (Eccentric) 2nd session	.966	12	.864
	Lt Peak torque (Eccentric) 3rd session	.960	12	.786
	Rt Peak torque/BW (Concentric) 1st session	.963	12	.829
	Rt Peak torque/BW (Concentric) 2nd session	.937	12	.456
	Rt Peak torque/BW (Concentric) 3rd session	.923	12	.314
	Lt Peak torque/BW (Concentric) 1st session	.964	12	.835
	Lt Peak torque/BW (Concentric) 2nd session	.893	12	.127
	Lt Peak torque/BW (Concentric) 3rd session	.852	12	.039
	Rt Peak torque/BW (Eccentric) 1st session	.945	12	.567
	Rt Peak torque/BW (Eccentric) 2nd session	.963	12	.826
	Rt Peak torque/BW (Eccentric) 3rd session	.944	12	.552
	Lt Peak torque/BW (Eccentric) 1st session	.959	12	.774
	Lt Peak torque/BW (Eccentric) 2nd session	.959	12	.767
	Lt Peak torque/BW (Eccentric) 3rd session	.967	12	.871
	Rt Work/BW (Concentric) 1st session	.979	12	.977
	Rt Work/BW (Concentric) 2nd session	.970	12	.915
	Rt Work/BW (Concentric) 3rd session	.979	12	.978
	Lt Work/BW (Concentric) 1st session	.976	12	.960
	Lt Work/BW (Concentric) 2nd session	.961	12	.803
	Lt Work/BW (Concentric) 3rd session	.991	12	1.000
	Rt Work/BW (Eccentric) 1st session	.884	12	.100
	Rt Work/BW (Eccentric) 2nd session	.919	12	.277
	Rt Work/BW (Eccentric) 3rd session	.932	12	.404
	Lt Work/BW (Eccentric) 1st session	.873	12	.071
	Lt Work/BW (Eccentric) 2nd session	.935	12	.431
	Lt Work/BW (Eccentric) 3rd session	.894	12	.134
Isokinetic Ankle Plantar Flexors	Rt Peak torque (Concentric) 1st session	.958	12	.750
	Rt Peak torque (Concentric) 2nd session	.960	12	.791
	Rt Peak torque (Concentric) 3rd session	.968	12	.888
	Lt Peak torque (Concentric) 1st session	.933	12	.409
	Lt Peak torque (Concentric) 2nd session	.944	12	.550
	Lt Peak torque (Concentric) 3rd session	.928	12	.358
	Rt Peak torque (Eccentric) 1st session	.948	12	.614
	Rt Peak torque (Eccentric) 2nd session	.967	12	.881
	Rt Peak torque (Eccentric) 3rd session	.966	12	.868
	Lt Peak torque (Eccentric) 1st session	.932	12	.401
	Lt Peak torque (Eccentric) 2nd session	.942	12	.528
	Lt Peak torque (Eccentric) 3rd session	.932	12	.400

	Rt Peak torque/BW (Concentric) 1st session	.955	12	.713
	Rt Peak torque/BW (Concentric) 2nd session	.961	12	.800
	Rt Peak torque/BW (Concentric) 3rd session	.945	12	.571
	Lt Peak torque/BW (Concentric) 1st session	.950	12	.640
	Lt Peak torque/BW (Concentric) 2nd session	.957	12	.740
	Lt Peak torque/BW (Concentric) 3rd session	.954	12	.700
	Rt Peak torque/BW (Eccentric) 1st session	.960	12	.783
	Rt Peak torque/BW (Eccentric) 2nd session	.962	12	.806
	Rt Peak torque/BW (Eccentric) 3rd session	.939	12	.487
	Lt Peak torque/BW (Eccentric) 1st session	.932	12	.407
	Lt Peak torque/BW (Eccentric) 2nd session	.960	12	.789
	Lt Peak torque/BW (Eccentric) 3rd session	.951	12	.657
	Rt Work/BW (Concentric) 1st session	.943	12	.534
	Rt Work/BW (Concentric) 2nd session	.942	12	.525
	Rt Work/BW (Concentric) 3rd session	.946	12	.575
	Lt Work/BW (Concentric) 1st session	.930	12	.377
	Lt Work/BW (Concentric) 2nd session	.925	12	.331
	Lt Work/BW (Concentric) 3rd session	.929	12	.374
	Rt Work/BW (Eccentric) 1st session	.958	12	.756
	Rt Work/BW (Eccentric) 2nd session	.958	12	.749
	Rt Work/BW (Eccentric) 3rd session	.973	12	.937
	Lt Work/BW (Eccentric) 1st session	.938	12	.472
	Lt Work/BW (Eccentric) 2nd session	.913	12	.230
	Lt Work/BW (Eccentric) 3rd session	.949	12	.617
Isokinetic Hip Extensors	Rt Peak torque (Concentric) 1st session	.958	12	.761
	Rt Peak torque (Concentric) 2nd session	.968	12	.884
	Rt Peak torque (Concentric) 3rd session	.937	12	.454
	Lt Peak torque (Concentric) 1st session	.946	12	.572
	Lt Peak torque (Concentric) 2nd session	.966	12	.861
	Lt Peak torque (Concentric) 3rd session	.929	12	.366
	Rt Peak torque (Eccentric) 1st session	.933	12	.415
	Rt Peak torque (Eccentric) 2nd session	.926	12	.339
	Rt Peak torque (Eccentric) 3rd session	.953	12	.678
	Lt Peak torque (Eccentric) 1st session	.973	12	.943
	Lt Peak torque (Eccentric) 2nd session	.960	12	.780
	Lt Peak torque (Eccentric) 3rd session	.967	12	.876
	Rt Peak torque/BW (Concentric) 1st session	.950	12	.639
	Rt Peak torque/BW (Concentric) 2nd session	.943	12	.534
	Rt Peak torque/BW (Concentric) 3rd session	.943	12	.541
	Lt Peak torque/BW (Concentric) 1st session	.947	12	.598
	Lt Peak torque/BW (Concentric) 2nd session	.945	12	.565
	Lt Peak torque/BW (Concentric) 3rd session	.950	12	.639
	Rt Peak torque/BW (Eccentric) 1st session	.947	12	.595
	Rt Peak torque/BW (Eccentric) 2nd session	.951	12	.647
	Rt Peak torque/BW (Eccentric) 3rd session	.950	12	.640
	Lt Peak torque/BW (Eccentric) 1st session	.957	12	.745
	Lt Peak torque/BW (Eccentric) 2nd session	.954	12	.701
	Lt Peak torque/BW (Eccentric) 3rd session	.949	12	.623

	Rt Work/BW (Concentric) 1st session	.919	12	.280
	Rt Work/BW (Concentric) 2nd session	.939	12	.491
	Rt Work/BW (Concentric) 3rd session	.938	12	.468
	Lt Work/BW (Concentric) 1st session	.881	12	.090
	Lt Work/BW (Concentric) 2nd session	.897	12	.147
	Lt Work/BW (Concentric) 3rd session	.895	12	.137
	Rt Work/BW (Eccentric) 1st session	.940	12	.501
	Rt Work/BW (Eccentric) 2nd session	.945	12	.563
	Rt Work/BW (Eccentric) 3rd session	.953	12	.676
	Lt Work/BW (Eccentric) 1st session	.949	12	.618
	Lt Work/BW (Eccentric) 2nd session	.956	12	.720
	Lt Work/BW (Eccentric) 3rd session	.956	12	.729

Appendix (C)

Appendix (C)

Tests of Normality for the Symmetry of Performance Across Tests Between Right and Left Legs Study

Test		Shapiro-Wilk		
		Statistic	df	Sig.
Hop	Rt single-leg horizontal hop for distance	.936	20	.200
	Lt single-leg horizontal hop for distance	.953	20	.423
	Rt crossover hop for distance	.944	20	.285
	Lt crossover hop for distance	.943	20	.268
2-D	Rt FPPA squat	.919	20	.096
	Lt FPPA squat	.951	20	.387
	Rt FPPA hop land	.914	20	.077
	Lt FPPA hop land	.951	20	.377
Balance	Rt straight leg balance	.972	20	.795
	Lt straight leg balance	.949	20	.354
	Rt bent leg balance	.900	20	.041
	Lt bent leg balance	.964	20	.628
	Rt leg TTS	.930	20	.155
	Lt leg TTS	.893	20	.031
Force (Squat Hop)	Rt Max RFD	.930	20	.153
	Lt Max RFD	.917	20	.088
	Rt Peak force	.979	20	.922
	Lt Peak force	.896	20	.035
	Rt Peak power	.960	20	.545
	Lt Peak power	.948	20	.332
	Rt Peak velocity	.950	20	.365
	Lt Peak velocity	.932	20	.168
Force (Countermovement Hop)	Rt Max RFD	.935	20	.189
	Lt Max RFD	.890	20	.026
	Rt Peak force	.975	20	.850
	Lt Peak force	.938	20	.222
	Rt Peak power	.959	20	.530
	Lt Peak power	.901	20	.043
	Rt Peak velocity	.949	20	.348
	Lt Peak velocity	.953	20	.420
Force (10 Hops)	Rt Max RFD	.939	20	.227
	Lt Max RFD	.921	20	.102
	Rt Peak force	.978	20	.905
	Lt Peak force	.946	20	.315
	Rt Peak power	.944	20	.286
	Lt Peak power	.965	20	.655
	Rt Peak velocity	.956	20	.459
	Lt Peak velocity	.944	20	.279
IMTP	Rt Max RFD	.958	20	.507
	Lt Max RFD	.891	20	.028
	Rt Peak force	.957	20	.483

	Lt Peak force	.971	20	.786
	Rt Impulse 0-100 ms	.976	20	.876
	Lt Impulse 0-100 ms	.716	20	.000
	Rt Impulse 0-200 ms	.970	20	.755
	Lt Impulse 0-200 ms	.828	20	.002
	Rt Impulse 0-250 ms	.953	20	.408
	Lt Impulse 0-250 ms	.859	20	.008
	Rt Impulse 0-300 ms	.960	20	.551
	Lt Impulse 0-300 ms	.918	20	.089
Isokinetic Quadriceps	Rt Peak torque (Concentric)	.854	20	.006
	Lt Peak torque (Concentric)	.880	20	.018
	Rt Peak torque (Eccentric)	.886	20	.023
	Lt Peak torque (Eccentric)	.887	20	.023
	Rt Peak torque/BW (Concentric)	.929	20	.146
	Lt Peak torque/BW (Concentric)	.949	20	.350
	Rt Peak torque/BW (Eccentric)	.915	20	.079
	Lt Peak torque/BW (Eccentric)	.935	20	.193
	Rt Work/BW (Concentric)	.956	20	.467
	Lt Work/BW (Concentric)	.958	20	.497
	Rt Work/BW (Eccentric)	.952	20	.404
	Lt Work/BW (Eccentric)	.966	20	.671
Isokinetic Hamstring	Rt Peak torque (Concentric)	.948	20	.344
	Lt Peak torque (Concentric)	.916	20	.083
	Rt Peak torque (Eccentric)	.946	20	.312
	Lt Peak torque (Eccentric)	.965	20	.638
	Rt Peak torque/BW (Concentric)	.985	20	.982
	Lt Peak torque/BW (Concentric)	.966	20	.662
	Rt Peak torque/BW (Eccentric)	.965	20	.649
	Lt Peak torque/BW (Eccentric)	.963	20	.612
	Rt Work/BW (Concentric)	.935	20	.189
	Lt Work/BW (Concentric)	.932	20	.172
	Rt Work/BW (Eccentric)	.893	20	.031
	Lt Work/BW (Eccentric)	.897	20	.037
Isokinetic Ankle Plantar Flexors	Rt Peak torque (Concentric)	.984	20	.975
	Lt Peak torque (Concentric)	.961	20	.563
	Rt Peak torque (Eccentric)	.972	20	.792
	Lt Peak torque (Eccentric)	.965	20	.639
	Rt Peak torque/BW (Concentric)	.984	20	.978
	Lt Peak torque/BW (Concentric)	.969	20	.725
	Rt Peak torque/BW (Eccentric)	.970	20	.746
	Lt Peak torque/BW (Eccentric)	.955	20	.458
	Rt Work/BW (Concentric)	.941	20	.252
	Lt Work/BW (Concentric)	.944	20	.285
	Rt Work/BW (Eccentric)	.975	20	.856
	Lt Work/BW (Eccentric)	.967	20	.695
Isokinetic Hip Extensors	Rt Peak torque (Concentric)	.925	20	.123
	Lt Peak torque (Concentric)	.933	20	.175
	Rt Peak torque (Eccentric)	.940	20	.237

	Lt Peak torque (Eccentric)	.954	20	.424
	Rt Peak torque/BW (Concentric)	.953	20	.421
	Lt Peak torque/BW (Concentric)	.971	20	.767
	Rt Peak torque/BW (Eccentric)	.942	20	.260
	Lt Peak torque/BW (Eccentric)	.945	20	.295
	Rt Work/BW (Concentric)	.956	20	.464
	Lt Work/BW (Concentric)	.918	20	.091
	Rt Work/BW (Eccentric)	.941	20	.249
	Lt Work/BW (Eccentric)	.954	20	.426

Appendix (D)

Appendix (D)

Tests of Normality for the Correlation Study (Healthy Participants)

Test		Shapiro-Wilk		
		Statistic	df	Sig.
Hop	Single-leg horizontal hop for distance	.975	65	.218
	Crossover hop for distance	.976	65	.240
2-D	FPPA squat	.914	65	.000
	FPPA hop land	.846	65	.000
Balance	Straight leg balance	.973	65	.159
	Bent leg balance	.946	65	.007
	Leg TTS	.980	65	.388
Force (Squat Hop)	Max RFD	.954	65	.017
	Peak force	.921	65	.000
	Peak power	.956	65	.021
	Peak velocity	.984	65	.567
Force (Countermovement Hop)	Max RFD	.891	65	.000
	Peak force	.786	65	.000
	Peak power	.949	65	.010
	Peak velocity	.955	65	.019
Force (10 Hops)	Max RFD	.981	65	.432
	Peak force	.975	65	.217
	Peak power	.990	65	.895
	Peak velocity	.988	65	.791
IMTP	Max RFD	.956	65	.021
	Peak force	.910	65	.000
	Impulse 0-100 ms	.625	65	.000
	Impulse 0-200 ms	.779	65	.000
	Impulse 0-250 ms	.758	65	.000
	Impulse 0-300 ms	.758	65	.000
Isokinetic Quadriceps	Peak torque (Concentric)	.947	65	.008
	Peak torque (Eccentric)	.966	65	.067
	Peak torque/BW (Concentric)	.987	65	.719
	Peak torque/BW (Eccentric)	.971	65	.128
	Work/BW (Concentric)	.965	65	.066
	Work/BW (Eccentric)	.959	65	.030
Isokinetic Hamstring	Peak torque (Concentric)	.947	65	.008
	Peak torque (Eccentric)	.927	65	.001
	Peak torque/BW (Concentric)	.982	65	.461
	Peak torque/BW (Eccentric)	.962	65	.042
	Work/BW (Concentric)	.928	65	.001
	Work/BW (Eccentric)	.938	65	.003
Isokinetic Ankle Plantar Flexors	Peak torque (Concentric)	.992	65	.962
	Peak torque (Eccentric)	.982	65	.481
	Peak torque/BW (Concentric)	.981	65	.428
	Peak torque/BW (Eccentric)	.976	65	.244
	Work/BW (Concentric)	.983	65	.517
	Work/BW (Eccentric)	.984	65	.562
Isokinetic Hip Extensors	Peak torque (Concentric)	.857	65	.000
	Peak torque (Eccentric)	.851	65	.000
	Peak torque/BW (Concentric)	.953	65	.016
	Peak torque/BW (Eccentric)	.942	65	.004
	Work/BW (Concentric)	.898	65	.000
	Work/BW (Eccentric)	.958	65	.026

Appendix (E)

Appendix (E)

ACLR Participants’ Invitation Letter

Knee Biomechanics and Injury Research
School of Health Sciences
University of Salford
Salford
Greater Manchester M6 6PU

Dear CLUB PHYSIOTHERAPIST

We are currently undertaking a research project investigating the outcome from ACL surgery. We are looking to undertake full biomechanical assessment on sports people who are 6-9 months post ACL surgery and about to return or who are already return to sport.

The biomechanical assessment will include 2D capture of squatting, landing, hopping, Limb stability, strength and force development tests will also be untaken. The aim is to provide a comprehensive overview of functional performance of ACLR patients prior to the return to sport or how are in risk of having injury for whom who are already retune to play. The project outline is attached.

The testing would take place in the University of Salford’s Human Performance Laboratory and lasts no longer than 2 hours. The project has been approved by the University research ethics committee.

Within 48 hours of testing you will receive a comprehensive report of the findings of the assessment with full explanation of those findings, and Dr Lee Herrington will also be available to discuss the implications of any of those findings with you and the athlete concern.

If you are interested in having your players tested or want any further information please do not hesitate to contact me on this email: H.S.Ghulam@edu.salford.ac.uk

I look forward to hearing from you.

Regards

Hussain Ghulam

Appendix (F)

Appendix (F1)

University of Salford MANCHESTER

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/

14 July 2014

Dear Hussain,

RE: ETHICS APPLICATION HSCR14/53 – What is Functional Performance of Anterior Cruciate Ligament (ACL) Reconstructed Patients prior to return to Sport?

Based on the information you provided, I am pleased to inform you that application HSCR14/53 has 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 (F2)

University of
Salford
MANCHESTER

Informed Consent Form

1. Hussain Ghulam, 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. ☐
2. My participation in this research will involve a number of tests include hopping, 2D capturing from squat and hop land, , limb stability, strength and force development tests will also be untaken. ☐
3. I understand the requirements of the study and my involvement and the possible benefit of my participation in this research. ☐
4. I have been informed that I will not be compensated for my participation. ☐
5. I understand that the results of this research may be published, but my name or identity will not be revealed at any time. In order to keep my records confidential, Hussain Ghulam will store all the data as numbered codes in a computer that will only be accessed by him. ☐
6. I have been informed that any further questions that I have at any time concerning the research or my participation will be answered by Hussain Ghulam and I can contact him at his e-mail address (H.S.Ghulam@edu.salford.ac.uk). ☐
7. I understand that I may withdraw my consent and participation at any time without objection from the researcher. ☐
8. I understand that if I withdraw from the study, all the information about me will be destroyed and not to be used in the study at all. ☐

Name: .... **Signed:** .... **Date:**

Appendix (G)

Appendix (G)

Tests of Normality for the Correlation Study (ACLR Participants)

Test		**Shapiro-Wilk**		
		Statistic	df	Sig.
Hop	Injured single-leg horizontal hop for distance	.984	33	.892
	Non-injured single-leg horizontal hop for distance	.990	33	.988
	Injured crossover hop for distance	.937	33	.056
	Non-injured crossover hop for distance	.955	33	.182
2-D	Injured FPPA squat	.958	33	.220
	Non-injured FPPA squat	.910	33	.010
	Injured FPPA hop land	.946	33	.100
	Non-injured FPPA hop land	.883	33	.002
Balance	Injured straight leg balance	.901	33	.006
	Non-injured straight leg balance	.965	33	.349
	Injured bent leg balance	.926	33	.027
	Non-injured bent leg balance	.889	33	.003
	Injured leg TTS	.801	33	.000
	Non-injured leg TTS	.699	33	.000
Force (10 Hops)	Injured Max RFD	.971	33	.508
	Non-injured Max RFD	.955	33	.185
	Injured peak force	.951	33	.141
	Non-injured peak force	.976	33	.650
	Injured peak power	.967	33	.391
	Non-injured peak power	.982	33	.832
	Injured peak velocity	.900	33	.020
	Non-injured peak velocity	.955	33	.185
IMTP	Injured max RFD	.932	33	.240
	Non-injured max RFD	.914	33	.078
	Injured peak force	.971	33	.507
	Non-injured peak force	.956	33	.200
	Injured impulse 0-100 ms	.825	33	.000
	Non-injured impulse 0-100 ms	.914	33	.078
	Injured impulse 0-200 ms	.705	33	.000
	Non-injured impulse 0-200 ms	.884	33	.012
	Injured impulse 0-250 ms	.801	33	.000
	Non-injured impulse 0-250 ms	.869	33	.006
	Injured impulse 0-300 ms	.861	33	.006
	Non-injured impulse 0-300 ms	.900	33	.030
Isokinetic Quadriceps	Injured peak torque (Concentric)	.864	33	.006
	Non-injured peak torque (Concentric)	.880	33	.012
	Injured peak torque (Eccentric)	.954	33	.170
	Non-injured peak torque (Eccentric)	.963	33	.311
	Injured peak torque/BW (Concentric)	.972	33	.551
	Non-injured peak torque/BW (Concentric)	.976	33	.662
	Injured peak torque/BW (Eccentric)	.974	33	.596

	Non-injured peak torque/BW (Eccentric)	.963	33	.320
	Injured work/BW (Concentric)	.922	33	.120
	Non-injured work/BW (Concentric)	.986	33	.942
	Injured work/BW (Eccentric)	.960	33	.257
	Non-injured work/BW (Eccentric)	.946	33	.103
Isokinetic Hamstring	Injured peak torque (Concentric)	.913	33	.072
	Non-injured peak torque (Concentric)	.920	33	.108
	Injured peak torque (Eccentric)	.903	33	.036
	Non-injured peak torque (Eccentric)	.906	33	.048
	Injured peak torque/BW (Concentric)	.960	33	.259
	Non-injured peak torque/BW (Concentric)	.972	33	.536
	Injured peak torque/BW (Eccentric)	.940	33	.069
	Non-injured peak torque/BW (Eccentric)	.934	33	.282
	Injured work/BW (Concentric)	.976	33	.671
	Non-injured work/BW (Concentric)	.940	33	.068
	Injured work/BW (Eccentric)	.915	33	.078
	Non-injured work/BW (Eccentric)	.850	33	.000