ONE-LEG HOP FOR DISTANCE IN THE ANTERIOR CRUCIATE LIGAMENT DEFICIENT POPULATION: DIAGNOSTIC ABILITY AND DETERMINANTS OF PERFORMANCE

by

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A thesis submitted in conformity with the requirements for the degree of Master of Science
Graduate Department of Rehabilitation Science
University of Toronto

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Master of Science 2001, Siobhán C. O’Donnell
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ABSTRACT

PURPOSE: To assess the impact that differences in inherent athletic ability (hop distance on the non-injured limb) has on the diagnostic validity of the hop index of the OLHD in assessing ACL injuries. To explore specific determinants of the OLHD and its association with perceived disability.

METHODS: OLHD, muscular function, confidence in landing and Mohtadi’s ACL-QOL questionnaire were evaluated in ten males with an isolated ACL tear and nine gender and age-matched Controls.

CONCLUSIONS: The distance hopped on the non-injured limb is a critical factor in the sensitivity of the hop index in the ACLD population. Transforming \((\log_{10})\) the hop distance scores to minimize the arithmetic variation between the proportional differences improves the sensitivity of the hop index. A decline in muscle function was associated with a decline in the ability to hop on the ACLD limb. Confidence and perceived disability were not associated with OLHD performance.
ACKNOWLEDGMENTS

This thesis would not have evolved without the assistance, support and dedication of many individuals throughout the past few years. I would like to take this opportunity to acknowledge the key individuals to whom I feel indebted.

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Finally, I would like to thank my husband, Mark MacNab, who so patiently endured dating and then being married to a Masters student! I thank-you for your love and encouragement.
DEDICATION

This thesis is dedicated to my parents whose love and support knows no bounds.
Thank-you mom and dad
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<td>Bio-Impedance Spectroscopy</td>
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<td>Body Weight</td>
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<td>Body Mass Index</td>
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CHAPTER 1
INTRODUCTION

Traditionally, the assessment of sports related knee ligament injuries has focused on various physical measures of impairment including ligamentous laxity, range of motion and strength [1, 2]. However, their usefulness has been challenged due to lack of a strong relationship with physical function and readiness to return to sports [3-6]. As a result, there has been a shift in emphasis from assessment of these physical impairments in the evaluation of patient’s knee status by way of tests of dynamic function.

Measures of lower extremity function play a key role in the assessment of patients with common sports related knee ligament injuries. The reliability of many of these tests has been established in terms of the consistency of patient scores. However, their validity has not been appropriately assessed with respect to specific applications pertaining to diagnosis, prognosis and responsiveness to treatment. Consequently, the interpretation of these tests is not standardized and is subject to variation across different patient populations, clinicians and settings. As a result, there is an urgent need to validate functional tests particularly in terms of their sensitivity in detecting lower limb functional limitations in the anterior cruciate ligament deficient (ACLD) population.

The anterior cruciate ligament (ACL) is the most commonly injured knee ligament, with an incidence of approximately 30 cases per 100,000 people per year [7]. The ACL functions as a primary stabilizer of the knee. Rupture of this ligament can be devastating to the athlete as the resulting instability may drastically alter their level of physical activity due to episodes of giving way, which most often occurs during demanding sporting activities. As a result, tests of knee function in this population attempt to mimic the physiological demands on the knee during athletic activities [4, 8].
A frequently employed test in the assessment of knee function in the ACLD population is the one leg hop for distance (OLHD). The demands on the knee provided by the OLHD are similar to that of many sports related activities such as running and jumping. In addition, the OLHD allows for an objective comparison of limb performance and requires minimal staff training, time and equipment to carry out [9-13].

The reliability of the OLHD has been well established through test re-test procedures [11, 12, 14-18] however, its diagnostic validity in the assessment of functional limitations in the ACL deficient has not been properly evaluated. To date, validity studies of the OLHD have revealed low sensitivity rates in detecting abnormal limb symmetry (hop index ≤85%) in the ACLD population [9, 13] nevertheless, these studies did not deal with the limitations associated with scoring the OLHD using the hop index. Two primary limitations related to scoring the OLHD include: 1) the differences in inherent athletic ability (note: the term inherent athletic ability is used throughout this thesis to define differences in hop distance on the non-injured limb only); and 2) the differences attributed to leg dominance when comparing the ACLD limb to an uninjured limb, for both within and between patient comparisons.

Furthermore, there is great uncertainty regarding the impairments associated with an ACL injury that are most influential in OLHD performance. In addition, the relationship between perceived disability and the OLHD has not yet been explored within an ACLD population.

First, this thesis will explore the usefulness of the OLHD as a diagnostic tool in the assessment of functional limitations in the ACL deficient and determine the impact that controlling for differences in inherent athletic ability and leg dominance has on the its diagnostic ability.
Second, an examination of the relationships between impairments (muscular function and confidence in landing) and OLHD performance was undertaken to foster a better understanding of the determinants of the OLHD in the ACLD. Furthermore, the relationship between the Quality of Life (QOL) Assessment in ACL Deficiency (ACL-QOL) scores and OLHD performance will be investigated to assess the association between perceived disability and lower limb functional performance in the ACLD.
CHAPTER 2
RELEVANT BACKGROUND

Knee injuries are the most common sports related injury and cause of permanent disability [7, 19]. The most prevalent type of knee pathology resulting from sports related injuries is ligamentous damage, accounting for up to 40% of all knee injuries [7]. With an incidence of approximately 30 cases per 100,000 people per year, the ACL is the most commonly injured knee ligament [7]. The ACL functions as a primary stabilizer of the knee; consequently, rupture of this ligament can be devastating to the athlete as the resulting instability may drastically alter their level of physical activity [19].

The integrity of the ACL is essential to the stability and protection of the knee joint and its periarticular structures [20]. Despite the secondary restraints that provide backup stability when this primary stabilizer is injured [21], instabilities of the knee may persist. Subsequent functional limitations in sporting activities predominate due to forces and displacements that the knee joint is subjected to when executing tasks such as running, jumping, rapid stopping, cutting and pivoting [22-25]. Hence, the ACLD athlete may have to modify their level of sports participation to minimize the risk of further injury and, as a result, are often disabled in their ability to play certain sports [26].

There are many clinical assessment tools used to evaluate physical impairments, functional limitations and perceived disabilities in the ACLD population. Unfortunately, these tools often provide conflicting results that make it difficult to determine the scope of the individual’s functional limitation and/or their readiness to return to pre-injury activities [27]. The focus of this review will be to examine how physical impairments, functional limitations and disabilities have been evaluated in the ACLD population. In addition, the relationships known to exist among the domains of impairment, functional limitation and disability will be reviewed. First a brief review
of the anatomy of the ACL, its role in knee function, mechanisms of injury, diagnostic measures and the natural history of chronic instability will be presented to facilitate an understanding of assessment measures used in the ACLD population.

2.1 ACL ANATOMY

Minimal stability is provided by the bony configuration of the knee joint; therefore, the knee depends on its many tendons and ligaments to maintain dynamic stability. Tendons connect muscle to bone and allow muscles to exert their actions on knee movement, whereas the ligaments connect bone to bone and are designed to check excessive or abnormal movement about the knee joint [21, 28, 29].

There are four major ligaments of the knee. These ligaments are situated both outside and within the joint capsule. Two are peripheral, extra-articular collateral ligaments that primarily resist varus (towards midline) and valgus (away from midline) stresses. The other two are central, intra-articular cruciate ligaments that predominately prevent abnormal anteroposterior tibiofemoral movements. The ACL is one of these two intra-articular ligaments and it crosses its partner, the posterior cruciate ligament (PCL), obliquely within the knee joint. The cruciate ligaments are named anterior and posterior according to their site of attachment on the tibia (see Figure 1) [21, 28-30].
2.1 Bony Attachments

The ACL originates from the anterior part of the intercondylar surface of the tibia and extends superiorly, posteriorly, and laterally to attach to the posterior part of the medial surface of the lateral femoral condyle [21, 30, 31]. The ACL fans out as it extends distally to the tibia, which results in a wider and stronger attachment on the tibia, compared to its attachment on the femur. A slip of the ACL has been observed to pass to the anterior horn of the lateral meniscus and in fewer cases, to the posterior horn of the lateral meniscus [31].

2.1.2 Fibre Arrangement and Dimensions

The ACL is a multifascicular structure and each fascicle is comprised of numerous interlacing collagen fibrils. The fascicles course through the knee in a spiral fashion and fan out as they attach to their tibial insertion [32, 33]. There exists some controversy regarding the number of bundles of fascicles that make up the ACL however, the majority of investigators have observed...
two physically distinct bands that are intimately connected. These bands, the anteromedial band (AMB) and a larger posterolateral band (PLB), apparently differ in function [31, 34, 35]. An intermediate component of the ACL has also been documented and represents the transition between the AMB and PLB [36, 37].

During knee flexion, the ACL twists onto itself, the AMB becomes taut and the PLB is somewhat lax. Whereas in knee extension, the ACL is flat, the AMB loosens and the PLB becomes tense [28, 31, 34]. Despite these distinct differences, it is important to note that the ACL is comprised of a continuum of fascicles where different portions are taut throughout knee range of motion.

This enables the ACL to remain functional in any given position [37].

![Figure 2](image_url)

**Figure 2**  ACL fibre arrangement and its changes in shape and tension as it undergoes extension (0° flexion) and flexion (90° flexion). The AMB (A-A') lengthens in flexion whereas the PLB (C-C') shortens. The intermediate component of the band (B-B') is situated between the AMB and PLB [37].
The reported mean length of the ACL varies among different investigators: Norwood and Cross (1979) 31mm; Kennedy, Weinberg and Wison (1974) 39mm and Boisgard, Levai, Geiger, Saidane and Landjerit (1999) 34.2mm [32, 38, 39]. The difference in lengths reported may be attributed to a number of factors. First, determination of the ACL length is challenging due to the fact its attachments are not only in orthogonal planes but are also displaced dorsoventrally [21]. Second, there were no gender distinctions made and consequently, differences due to gender are unknown. Third, measurement methods varied from using adult cadaver knees [32, 38] to a 3-dimensional computerized model of the knee in a living subject [39]. Finally, some investigators reported the mean ACL length at a specific knee position [32, 38] while others averaged the lengths obtained at varying degrees of knee flexion [39]. Nevertheless, of those investigators who measured the average length of each of the three bundles concur that the length of the AMB exceeds that of the other two bundles [38, 39].

2.1.3 Vascular and Nerve Supply

The network of vessels permeating the ACL is derived predominately from the synovium that envelops the ligament. These vessels originate from the middle genicular artery and give rise to smaller connecting branches, which penetrate the ligament transversely and anastomose with a network of endoligamentous vessels [21, 37]. However, due to the sparse intra-ligament blood circulation, the ability of the ACL to heal if injured is very poor [40].

Nerve fibres that originate from the tibial nerve pierce the joint capsule posteriorly to supply the ACL. These fibres course alongside of the synovial and periligamentous vessels that surround the ligament. Smaller nerve fibres have been found throughout the ligament itself. The bulk of the fibres appear to have a vasomotor function though it has been suggested that the fibres found among the fascicles of the ligament serve more of a proprioceptive function [37].
2.2 ROLE OF THE ACL IN KNEE FUNCTION

The majority of knee joint stability depends upon the major ligaments of the knee. Ligaments of the knee function as mechanical restraints, passively resisting tensile loads to prevent excessive motion in the joint's normal planes of movement and restrict abnormal movements in directions that the joint is not designed to move [19]. In addition, the ligaments of the knee may play an active role in maintaining joint stability by providing important neurologic feedback that mediates joint position sense and muscular reflex stability [41].

When describing the role of the ACL as a mechanical stabilizer of the knee joint, it is useful to consider its role as a primary, versus a secondary, ligament restraint. A primary restraint provides the majority of resistance to a specific joint displacement whereas a secondary restraint contributes less resistance. Nevertheless, both primary and secondary ligament restraints work together to provide knee joint stability [25, 42].

The function of the ACL in maintaining knee joint stability has been profiled in biomechanical studies on cadaveric specimens. There is consensus that the ACL is the major restraint controlling anterior translation of the tibia on the femur however, the ACL also plays a significant role in other types of knee motion [42].

Most experimental studies performed selective cutting of the ACL in which measurements of the different displacements under manual stress were taken. When the entire ACL was selectively cut, an increase in the anterior displacement of the tibia on the femur in flexion and extension was observed [28, 31, 34, 36, 43]. However, the degree of displacement measured with selective cutting of a ligament is dependent on the order of ligament dissection making it impossible to define the function of a single ligament precisely [44]. By applying a known anterior displacement to the tibia while measuring the restraining force, Butler, Noyes and
Grood (1980) defined the contribution of each ligament by the reduction in total restraining force that occurs after ligament sectioning. Using this method, they confirmed that the ACL is the primary restraint to anterior tibial translation as it provides 86% of the total resisting force, whereas the secondary restraints (ligaments and capsular structures), provided the remaining restraining force which amounted to less than 3% each [44].

The ACL acts as a secondary restraint in the movements of: extension and hyperextension [28, 31, 32, 34]; tibial rotation [28, 31, 32, 34, 36, 43]; varus and valgus stresses [28, 43] and the ACL assists in the “final compulsory rotation” of Fick [28].

The “final compulsory rotation” of Fick occurs in terminal extension of the knee joint and is controlled in part by the cruciate ligaments. Due to its shorter anterior-posterior length, the lateral femoral condyle completes its movement into extension prior to the medial femoral condyle. Tightening of the ACL and lateral collateral ligament in extension anchors the lateral aspect of the joint anteriorly which allows the medial femoral condyle time to complete its movement by “skidding” backward as the femur rotates medially. This results in a final tightening of all the ligaments and locking of the knee joint [28].

Identification of sensory receptors (Ruffini endings, Pacinian corpuscles, Golgi tendon-organ like endings and free nerve endings) within the ACL has lead investigators to believe that the stability of the knee joint is not only mediated by the passive mechanical restraints, but also by neurologic input. These receptors have different means of providing the central nervous system with information regarding static joint position, intra-articular pressure, amplitude and velocity of movement, position-related stress of the ligament and noxious and chemical events [45]. Clinical evidence of the neuromuscular deficits associated with an ACLD knee include: diminished sense of position and movement of the knee; altered ligament-muscle reflex; altered
muscle stiffness; quadriceps-force deficit; altered muscular activation patterns and functional adaptations [46]. However, conflicting results prevail among studies where investigators have attempted to measure specific neuromuscular changes within ACLD knees which may be due in part to differences in the parameters tested, the method of measurement and different patient populations. Nevertheless, as more sensitive measures are developed, we will gain a better understanding of the actual role of the sensory receptors within the ACL [46].

2.3 MECHANISM OF INJURY
The ACL is inherently strong and can resist forces as high as 2195 Newtons (N) before failure [47-49], while loads applied to the ACL during activities of daily living have been estimated to be only 445N [47, 50]. Despite its tensile strength, the ACL possesses limited intrinsic elasticity as an application of force straining the ACL by more than 5 percent of its resting length will result in a rupture [40]. Typically, the ACL sustains a midsubstance tear, which is a central ligament tear, as opposed to a tear of the ligament at one of the site of its bony attachments [19].

Figure 3 A complete midsubstance tear of the ACL [51].
The mechanism of injury is a result of either contact or non-contact forces. Contact injuries involve external forces. Whereas non-contact injuries usually occur during deceleration of the body and/or a twisting maneuver, for instance when the foot is planted and a change in direction of the femur on the tibia occurs [52]. Such insults to the knee most commonly occur in high velocity sporting activities [24, 40].

The severity of injury to the ACL depends upon the magnitude, speed and direction of the force applied. And due to the forces involved, an isolated rupture of the ACL is uncommon (only 20% to 35% of all cases) [53-55]. Understanding the mechanism of injury can assist in ascertaining both the ACL and support structure involvement in the event of a knee injury.

There appear to be four distinct mechanisms by which the ACL is injured. The most common involves deceleration of the body in a non-contact situation. The knee is in slight flexion to full extension as the quadriceps contract eccentrically to decelerate the body. This creates an anterior shear of the tibia on the femur that is restrained by the ACL and the hamstring musculature. Further stress is placed on the ACL if the femur is externally rotated with the tibia in internal rotation. This could occur as the athlete rotates or changes direction with the foot planted [19, 24, 32, 40, 52].

Another mechanism of injury involves hyperextension of the knee, which can result with or without an external force applied. The PCL is usually ruptured prior to the ACL in the instance of pure hyperextension however, isolated injuries to the ACL have been associated with forced hyperextension when combined with internal rotation of the tibia. Either an anterior blow to the femur or a forceful quadriceps contraction can result in a hyperextension injury of the knee [20, 24, 29, 32, 40, 57].
Two less common mechanisms of injury to the ACL are hyperflexion of the knee joint [20, 57] and knee flexion with external rotation of the tibia. This latter mechanism is further compounded by the addition of a valgus stress to the lateral aspect of the knee and usually involves injury to the medial capsule and the medial collateral ligament before the ACL [20, 32, 58].

2.4 DIAGNOSTIC MEASURES

Early detection of an ACL injury is important in order to facilitate the most appropriate intervention as early as possible to minimize loss of function. A variety of approaches can be used to assist in the diagnosis of an injury to the ACL. These include taking a complete and accurate patient history, manual and arthrometer tests of ligament laxity, magnetic resonance imaging (MRI) and arthroscopic investigation [19, 59].

Accurate history taking, which includes the patient’s mechanism of injury and signs and symptoms, are key in the diagnosis of an ACL injury [24, 60, 61]. McNair, Marshall and Matheson (1990) investigated the mechanism of injury and signs and symptoms associated with the initial injury to the ACL in 23 subjects. The mechanism of injury, although variable, reflected the fundamental role of the ligament in restraining anterior displacement, and internal and external rotation to lesser degrees. However, the investigators stated that detection of an ACL injury, based on information regarding the mechanism of injury alone, is difficult due to the fact that the mechanisms involved in a meniscal injury are very similar. Therefore, in addition to information regarding the mechanism of injury, knowledge regarding the signs and symptoms at time of injury was felt to greatly increase the probability of establishing a correct diagnosis. The signs and symptoms deemed most relevant to an ACL tear were: a crack or popping sound at the time of injury; a shifting sensation between the tibia and femur; falling to the ground; an inability to continue in the given activity and rapid effusion [24].
Manual ligament laxity tests are the primary means by which clinicians assess ACL injuries [23, 62]. Many different ACL laxity tests have been defined and their main purpose is to determine the presence and degree of ligamentous laxity. To ensure the proper usage of this type of assessment tool, it is essential that the general limitations of the manual laxity tests be understood. First, the clinician must make a subjective assessment whether or not the manual laxity test is positive or negative, and if the test is positive, to what extent. Hence, the accuracy of manual laxity tests is largely dependent upon the skill and experience of the examiner. Second, the use of small test forces may allow abnormal laxity to go undetected. Third, the presence of taut secondary restraints, muscle spasm, pain, swelling or difficulty getting the patient to relax (often symptoms of an acute injury) may conceal abnormal laxity results [23, 59, 63-65]. For further discussion regarding the specific manual tests used in this study see Chapter 2, Section 2.6.1.

A knee ligament arthrometer is an instrumented clinical knee-testing device used to measure anterior-posterior knee ligament instability. This instrument was designed to improve the objectivity of ligamentous stress testing. It provides an objective and non-invasive means of measuring the anteroposterior displacement in millimeters at a given force; however, it does not allow for measurement of rotational, valgus or varus displacements [66]. The diagnostic accuracy of this tool is variable and dependent upon many factors for instance, the amount of knee flexion, tightness of the strap, patellar stabilization, placement of the arthrometer with reference to the joint line and the degree of tibial rotation, may all affect the results [66, 67]. In addition, the acuity or chronicity of the injury may affect a correct diagnosis as chronic cases more often produce positive results because of less pain, muscle spasm, swelling and patient apprehension [63]. Furthermore, the protocol used in the assessment of the anterior laxity in the ACLD knee may affect the accuracy of the diagnosis. A study conducted by Daniel, Stone, Sachs and Malcom (1994) assessed the diagnostic accuracy of three different protocols using a
knee joint arthrometer in the assessment of ACL injuries: 1) anterior displacement between a 15 and 20 pound force (compliance index); 2) anterior displacement with a 20 pound force and 3) anterior displacement with a maximum manually applied force. The accuracy of detecting abnormal anterior laxity in the ACLD knees ranged from 62% to 91% with the maximum manual test being the most sensitive of the three protocols [68].

MRIs have proven to be a useful diagnostic tool in the evaluation of the integrity of the ACL [69, 70]. This non-invasive form of evaluation allows for observation of the entire ACL, including its sites of attachment, without manipulation of the knee. In addition, MRIs provide a means to evaluate the integrity of other ligaments and the menisci [69]. Diagnosis of an injury to the ACL using an MRI is based on changes in the intensity of the signal, lack of continuity and distorted relationships as the ACL courses intra articularly in the knee joint [70]. The diagnostic accuracy of MRIs is high, ranging from 93 to 100 per cent [69, 70] however, it is a costly procedure [19].

Arthroscopic surgery is a diagnostic procedure that enables the observation of the ACL through the use of an endoscope that is inserted into the knee through a small incision. Due to the fact that this is an invasive and costly procedure it is not used as a front line diagnostic tool. However, it often used as the gold standard in the evaluation of the accuracy of other diagnostic tools in the detection of an ACL tear [63, 67, 69, 70] as the ACL can be well visualized via an endoscope [71].

2.5 NATURAL HISTORY OF CHRONIC ACL INSTABILITY

Variability in the natural history has lead to considerable debate regarding the fate of the ACLD individual [26, 56]. However according to Noyes, McGinniss and Grood (1985) the joint at risk is dependent upon various risk factors including: the severity of initial injury; episodes of re-injury
or recurrent giving-way; activity level and goals; meniscal pathology; recurrent joint effusions; neuromuscular skills and compliance with a rehabilitation program [26].

An individual with a symptomatic ACLD knee most commonly complains of pain. Pain can be experienced at various different activity levels (i.e. during activities of daily living or strenuous activities) and is often experienced during an episode of giving way. The second most common complaint is that of giving way. Giving way is a feeling of instability about the knee as if the knee were to buckle. This symptom can also occur at different activity levels but most commonly occurs during strenuous activities (i.e. sports that involve twisting, cutting, jumping or rapid deceleration). The third most common symptom is swelling. Swelling is usually minor and occurs with activity. The presence of swelling during demanding or prolonged activities may be a sign of developing osteoarthritis [56].

Recurrent bouts of giving way (as few as two to three times per year) may lead to damage of the periarticular structures over time [26]. Fetto and Marshall (1980) showed that the severity of anteriorposterior and rotational instability increased with time. This progressive laxity of the periarticular structures (which act as a compensatory mechanism for joint stability) has been suggested to compromise functional stability, resulting in an increase in the incidence of giving way [20].

An acute isolated injury to the ACL is frequently compounded by meniscal tears, which occur in up to 77% of cases. The menisci distribute synovial fluid and nutrients, assist in knee stability and decrease stress to the articular surface of the joint by redistributing the load and acting as a shock absorber. Therefore, the integrity of the menisci is very important to the ACLD knee. Recurrent bouts of giving way or re-injury put the menisci at risk of tears which can result in damage to the articular surfaces of the knee joint over time [56, 72].
As a rule, activity levels are reduced after an ACL injury. The reduction in activity may be evident in activities of daily living or apparent only during demanding sporting activities [20, 61, 67]. However, the change in activity level is difficult to accurately assess as some individuals may return to their pre-injury activities but may modify their behavior or alter their performance. Others return to their pre-injury activities, but due to an increase in symptomatology over time, may decrease their level of participation. While some modify their activity level immediately post-injury, they may eventually return to their pre-injury activities [56]. Further difficulty in determining a change in activity arises when activity levels are modified as a result of a lifestyle change as opposed to a functional limitation imposed by the knee injury [67]. Nevertheless, individuals who continue to participate in highly demanding sports, in spite of repeated bouts of giving way, increase the risk of sustaining new injuries that may increase the rate of degenerative changes [26, 53, 56].

The reported incidence of radiographic degenerative joint changes in ACL injuries varies from 20 to 88% [56, 72]. Partial ACL tears appear to be associated with a smaller risk of developing degenerative changes (15 to 20%) compared to complete tears (up to 70%) [53]. The risk of developing degenerative joint disease and its rate of progression appears to be dependent upon the severity of initial injury, in addition to other factors such as: the release of cytokines (breakdown products of cartilage and markers of cartilage matrix metabolism) following the injury; subsequent meniscal tears; further ligamentous injury; chondral lesions; meniscal removal; lower extremity malalignment; biologic factors (i.e. gene variations and mutations) and the trauma of surgery [53, 56, 72]. However, degenerative changes reported 10 to 20 years after ACL injury are usually not associated with major clinical symptoms. Due to this slow progression, problems related to degenerative joint disease may not require treatment for years (> 30) after the initial injury [53].
2.6 IMPAIRMENTS

According to the National Centre for Medical Rehabilitation Research's (NCMRR) modified version of Nagi's disablement model (1991), the term 'impairment' implies a loss or abnormality of cognitive, emotional, physiological, or anatomical structure or function [73]. This section will review anthropometric measures used to assess level of fitness and measures of evaluation for specific physical impairments as a result of ACL injury including: ligamentous laxity, muscle function and fear of subluxation on landing the OLHD. In addition, the International Knee Documentation Committee (IKDC) Knee Ligament Standard Evaluation will be discussed in this section since the majority of its components evaluate various physical impairments.

2.6.1 Anthropometric Measures

Height, weight (BWT), average leg length, body mass index (BMI), waist (abdomen) girth, % of body fat and fat free mass (FFM) are important anthropometric measures in the description and comparison of different populations. In addition, the assessment of body composition via measures such as BMI, waist girth, % of body fat and FFM provide insight into level of fitness.

BMI is a measure of proportional BWT and is determined by dividing BWT by height squared (kgm\(^2\)) [74]. High BMI values may be a result of a high proportion of adipose tissue (fat) or a high proportion of lean body mass (muscle) therefore, an accurate interpretation of body composition is gained through observation and/or other anthropometric measures such as waist girth. Waist girth (measurement of the waist or abdomen) is another measure of adiposity and it lends insight into the location and extent of fat tissue present. The Canadian Physical Activity, Fitness and Lifestyle Appraisal (CPAFLA) guidelines provide a means by which one can interpret both BMI and waist girth measurements based on data from the Canada Fitness Survey (1981) and trends in morbidity and mortality data [74].
Bio-Impedance Spectroscopy (BIS) can enhance the assessment of body composition by providing information on the % of body fat and FFM. It permits a safe, non-invasive and portable method for estimating the intra and extra cellular fluid volumes through an analysis of the reactance and resistance of a mild alternating electrical current from which measures of body composition are estimated using mathematical equations [75, 76].

Validation studies of the Hydra ECF/ICF Bio-Impedance Spectrum Analyzer (Xitron Technologies Inc., San Diego, CA) have been conducted on young to middle age healthy subjects using an earlier device (Model 4000B) to that used in the present study (Model 4200) [75, 76].

Van Loan, Withers, Mathi and Mayclin (1993) compared the BIS estimates of total body water (TBW), ECF, ICF and FFM to standard laboratory methods in a group of healthy men (n=10) and women (n=14) (mean age ± SD, 29.9± 6.7 years). Results revealed high correlation's between BIS predicted and dilution determined TBW (r=0.92; SEE=2.28L); ECF (r=0.89; SEE=0.95L) and ICF (r=0.88; SEE=1.99L) in addition, a high BIS predicted and densitometry determined FFM (r=0.94; SEE=2.59kg) [76].

De Lorenzo, Andreoli, Mat!hie and Withers (1997) validation research demonstrated similar results to Van Loan et al. (1993) in a group of 87 healthy Italian men (n=77) and women (n=10) who ranged in age from 21 to 57 years. In a sub-group of 14 men, the BIS TBW, ECF and ICF prediction of dilution determined TBW, ECF and ICF was r=0.95, SEE=1.33L; r=0.91, SEE 0.90L and r=0.87, SEE 1.69L, respectively. In addition, the BIS ICF prediction of the total body potassium in 73 subjects was r= 0.85, SEE= 2.22L [75].
Cross validation of the Hydra ECF/ICF (Model 4200) Bio-Impedance Spectrum Analyzer with other technologies/equations found within the literature was not carried out since the estimates of body composition were included to compare ACLD and healthy, non-injured Controls and any measurement error was assumed to be equal across groups.

The test re-test measurement of BIS estimates of body composition have been demonstrated in ideal test conditions [76]; however, various measurement and biological factors can affect the accuracy of the body composition estimates. Therefore, strict adherence to the manufacturer's measurement instructions is critical to ensure ideal test conditions.

**2.6.2 Ligamentous Laxity in the ACLD**

When discussing ACL injuries it is important to distinguish between ligamentous laxity and joint instability. The term ‘laxity’ refers to the slackness of a ligament. A certain amount of laxity is normal therefore, it is essential to determine normal versus abnormal displacement of the joint by evaluating the non-injured knee first to establish a baseline for comparison. While, the term ‘instability’ is used to describe excessive or abnormal joint motion and is usually the result of numerous factors in which abnormal ligamentous laxity is one possible cause [59]. Therefore, rupture of the ACL results in abnormal ligamentous laxity of the knee that can result in functional instability.

There are many manual ligamentous laxity tests used to assess the integrity of the ACL. The purpose of this testing is twofold: 1) to determine the presence of abnormal laxity, and 2) to determine the degree of laxity. The different ACL laxity tests can be classified as those that assess abnormal anterior tibial displacements and those that assess for the presence of a ‘pivot shift’. For general limitations of manual laxity tests see Chapter 2, Section 2.4.
The ACL laxity tests investigated in this thesis are specific to the ligament evaluation component of the IKDC Ligament Standard Evaluation which includes the three most commonly used tests: anterior drawer, Lachman and pivot shift [55, 65] as well as the reverse pivot shift. The anterior drawer and Lachman are designed to assess abnormal anterior tibial displacements, whereas the pivot shift and reverse pivot shift are designed to elicit the pivot shift phenomenon from the ACLD knee [59].

The diagnostic accuracy (sensitivity) of the anterior drawer, Lachman and pivot shift tests are well documented however, no scientific studies on the accuracy of the reverse pivot shift test were found in the literature (Table 1).

There is consensus among investigators that the Lachman test is the most sensitive clinical test for acute and chronic ACL tears [54, 55, 64, 65, 77, 78]. Whereas, most concur that the anterior drawer and the pivot shift test are less sensitive in acute cases although their diagnostic accuracy improves in the assessment of chronic cases or when the investigation is carried out under anesthesia [54, 55, 64, 65, 77, 78]. The technique and limitations specific to the anterior drawer, Lachman, pivot shift and reverse pivot shift and method of grading will be discussed.
### Summary of the Sensitivity Rates of ACL Manual Laxity Tests cited within the Literature

<table>
<thead>
<tr>
<th>Investigator (Year)</th>
<th>Subjects</th>
<th>Anterior Drawer</th>
<th>Lachman</th>
<th>Pivot Shift</th>
</tr>
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<tbody>
<tr>
<td>DeHaven (1980)</td>
<td>N=35 acute complete ACL tears combined with meniscal injuries</td>
<td>9% no anesthesia 52% with anesthesia</td>
<td>80% no anesthesia 100% with anesthesia</td>
<td>9% no anesthesia 63% with anesthesia</td>
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<tr>
<td>Donaldson et al. (1985)</td>
<td>N=64 acute complete ACL tears combined with meniscal &amp;/or collateral ligament injuries  N=37 acute complete isolated ACL tears</td>
<td>70% no anesthesia 91% with anesthesia</td>
<td>99% no anesthesia 100% with anesthesia</td>
<td>35% no anesthesia 98% with anesthesia</td>
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<tr>
<td>Jonsson et al. (1982)</td>
<td>N=45 acute ACL tears N= 62 chronic ACL tears  Total =107 (105/107 combined with meniscal &amp;/or collateral ligament injuries and 2/107 with an isolated ACL injury. No mention of whether the ACL tears were partial or complete)</td>
<td>33.3% no anesthesia 97.8% with anesthesia</td>
<td>86.7% no anesthesia 100% with anesthesia</td>
<td>Not Investigated</td>
</tr>
<tr>
<td>Liu et al. (1995)</td>
<td>N=38 acute complete ACL tears (no mention of whether there were associated injuries)</td>
<td>61% no anesthesia</td>
<td>95% no anesthesia</td>
<td>71% no anesthesia</td>
</tr>
<tr>
<td>Kim et al. (1995)</td>
<td>N=147 chronic complete ACL tears (111/147 combined with meniscal &amp;/or collateral ligament injuries and 36/147 with an isolated ACL injury). Those with a partial ACL tear and marked medial laxity were excluded.</td>
<td>79.6% with anesthesia</td>
<td>98.6% with anesthesia</td>
<td>89.8% with anesthesia</td>
</tr>
<tr>
<td>Torg et al. (1976)</td>
<td>N=93 combined tears of the ACL &amp; medial meniscus without valgus laxity</td>
<td>40% “pre-operatively” (no mention if testing was performed with or without anesthesia)</td>
<td>95% “pre-operatively” (no mention if testing was performed with or without anesthesia)</td>
<td>Not investigated</td>
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<tr>
<td></td>
<td>N=43 combined tears of the ACL &amp; medial meniscus without valgus laxity</td>
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<td></td>
<td>(no mention of whether the ACL tears were partial Vs complete or acute Vs chronic)</td>
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**Table 1** Summary of studies that investigated the diagnostic accuracy of clinical ACL manual laxity tests in the ACLD population
2.6.2.1 **Anterior Drawer Test**

The anterior drawer test is performed with the patient lying supine, hip flexed to 45°, knee flexed to 90° and the foot flat on the table which may be stabilized by having the clinician sit on it. The clinician grasps the posterior aspect of the tibia with both hands, resting the thumbs across the anterior joint line, while the fingers palpate the hamstring tendons to ensure no tone or protective spasm. An anterior force is then applied to the posterior aspect of the proximal tibia. The test is considered positive if proprioceptive and/or visual anterior translation of the tibia in relation to the femur is greater in the affected knee [22]. The anterior drawer test can also be performed with the tibia internally or externally rotated to assess the integrity of the collaterals, the illiotibial band and other tertiary capsular restraints [22, 79].

This test is relatively easy to perform by clinicians of any size or strength and on any size of patient. Despite this, investigators have deemed it to be an unreliable diagnostic tool [78]. Factors that could cause a false negative drawer sign include: a hemarthrosis or pain that prevents flexion of the knee to 90°; protective hamstrings which may be sufficient to limit the anterior translation of the tibia; reattachment of the ACL to the PCL [55]; wedging of the posterior horns of the menisci between the femoral and tibial condyles thus blocking the anterior translation of the tibia [78]; and in the event of a partial tear [34, 80]. Conversely, a false positive anterior drawer test can occur due to missed tibial sagging in PCL injuries [44, 62].

2.6.2.2 **Lachman Test**

The Lachman test is carried out with the patient supine with the knee held between 15° and 20° of flexion, the femur stabilized with one hand while firm pressure is applied to the posterior aspect of the proximal tibia in an attempt to translate it anteriorly [59]. The test is considered positive if proprioceptive and/or visual anterior translation of the tibia in relation to the femur is greater in the affected knee with a mushy or soft endpoint [78].
The strength of the Lachman test lies in the fact that the patient’s knee is tested in a position of comfort and less muscle guarding. In addition, the flat configuration of the articulating surfaces in this degree of knee flexion does not obstruct forward motion of the tibia [23, 78].

False negative Lachman tests can occur when: the knee is incorrectly positioned since decreasing the flexion from 30° to 10° may result in minimal excursion and a false endpoint [64]; the girth of the thigh is so large and/or the examiner’s hands are small, preventing proper force applications [81]; reattachment of the ACL to the PCL has occurred [55]; an inappropriate amount of rotation is applied to the tibia during the administration of the test [79]; a displaced bucket handle tear of the medial meniscus blocks translations [55, 78] and in the case of a partial tear [64, 80]. Conversely, a false positive Lachman test could occur when there is injury to the PCL as a result of restoring the tibia to its neutral position from a drop-back position, which may also occur in the performance of the anterior drawer test [64].

2.6.2.3 Pivot Shift Test

The term ‘pivot shift’ was coined by Galway, Beaupre and Maclntosh in 1972 for the subjective description used by the patient to describe the sequence of the “knee going out” [82]. The pivot shift phenomenon is primarily due to anterolateral rotatory instability of the knee and the pivot shift test (also known as the MacIntosh test) was the first test to elicit this phenomenon. With the knee in extension, a valgus stress is applied to the proximal tibia, and the foot is internally rotated. The knee is then slowly flexed. The lateral tibial plateau subluxes forward gradually as the knee comes out of the “locked home” position. When it reaches approximately 20 to 40° of flexion, there is a sudden reduction of the tibia that is produced by the iliotibial tract as it moves posteriorly and pulls on the lateral tibial plateau causing it to externally rotate and reduce. The valgus thrust to the knee is used to enhance the velocity of the reduction and to accentuate the jerk, as does weight bearing [23, 59].
The pivot test has been found to be most useful in diagnosing an ACL tear in chronic cases or when the investigation is carried out under anesthesia [54, 55, 64, 77]. False negative results can occur in the instance of: pain; limited knee extension; muscle guarding [54]; medial collateral ligament laxity [55, 64]; a partial tear of the ACL [64, 80]; after a meniscectomy, as the tibia slips beneath the femur without sudden jump [20]; reattachment of the ACL to the PCL; a bucket handle tear of the meniscus; tightness of the lateral compartment [55] and the skill/technique of the examiner (the pivot shift is more challenging in its administration and interpretation relative to the Lachman or anterior drawer test) [83].

2.6.2.4 Reverse Pivot Shift Test

The reverse pivot shift is primarily due to posteriolateral rotatory instability and is not as common as anterolateral instability. This type of instability involves the supporting structures of the posterolateral aspect of the joint, as well as the cruciate ligaments to a varying degree. The reverse pivot shift test is carried out by providing a valgus stress to accentuate the moment of reduction and subluxation as the knee is extended with the foot in external rotation, there is a sudden reduction as the lateral tibial plateau moves from its posterolateral position. Since the pivot shift and the reverse pivot shift tests both produce a sudden event with reduction and subluxation, it can be difficult to identify which way the tibia is abnormally moving. Therefore, additional tests to confirm the involved ligament(s) are necessary [23].

2.6.2.5 Grading of ACL Laxity

According to the Hughston classification system for quantifying knee joint laxity, ACL injuries are categorized as either a grade 1+, 2+ or 3+ according to the degree of instability. Where 0 to 5 millimeters (mm) of anterior posterior laxity is considered a grade 1+, 5 to 10 mm is classified as a grade 2+, and greater than 10mm is categorized as a grade 3+ [22]. The ligament examination component of the IKDC knee ligament standard evaluation utilizes the Hughston
classification system for quantifying knee joint laxity and defines grades 1+, 2+ and 3+ as “Nearly Normal”, “Abnormal” and “Severely Abnormal” respectively.

2.6.3 Decreased Muscular Function

General thigh muscle atrophy, changes in the quadriceps-hamstrings relationship in cross-sectional areas of the thigh and strength deficits have been well documented in the ACLD knee [84-87]. Studies of the cross-sectional areas of atrophied thigh muscles using computerized tomography have demonstrated that atrophy is greater in the quadriceps than the hamstrings after knee ligament injury [87]. In support of this, clinical trials that have evaluated thigh muscle strength in ACLD individuals have demonstrated that muscle deficits are greater in the quadriceps versus the hamstring muscles in chronic ACLD knees [84-86]. In fact, Murray, Warren, Otis, Kroll and Wickiewicz (1984) documented an overall extensor torque deficit of 12% and overall flexion torque deficit of 7% in patients with isolated ACL tears after six months of intensive rehabilitation which implies that these deficits are difficult to eliminate post ACL injury [84].

The assessment of muscular function can be conducted in many different ways. An explanation of the types of muscular contractions, methods of assessment and the indications/limitations of each will be discussed.

Muscular strength, the ability of a muscle to exert a force [88], can be generated in three different ways: isometrically, isotonically and isokinetically. An isometric contraction is static in nature and results in an increase in muscular tension; however, there is no visible change in length of the muscle or joint motion. Isotonic (fixed load, changing angular velocity) and isokinetic (fixed angular velocity, changing load) contractions are dynamic and result in the movement of a joint or body part. Isotonic and isokinetic contractions can be either concentric
and/or eccentric in nature. A concentric contraction, results in an overall shortening of the muscle as it generates tension whereas an eccentric contraction results from an overall lengthening of the muscle as it contracts to control motion performed by an outside force [89, 90].

Isometric muscular strength is measured using cable tensiometer or non-motorized dynamometer. However, since both devices record muscular force during a static or isometric contraction they cannot provide information regarding dynamic muscular strength required in daily activities or sports [91].

Isotonic muscle function testing involves a multi-joint movement, allows for changes in the angular velocity throughout the range of motion and a natural concentric/eccentric component which more closely approximates human functional movement [89, 93]. However, it is difficult to standardized movement velocity and muscular compensations, which may confound test results [88, 91].

A repetition maximum test, by way of free weights or weight-training machines, is commonly used in the assessment of isotonic muscular strength [91, 92]. The one-repetition maximum (RM) method assesses strength by determining the maximal weight or resistance that can be moved through a range of motion once.

The one RM leg press has proven to be a reliable and valid measure of isotonic lower extremity strength. Test reliabilities of r=0.84 to 0.92 have been cited for the one RM lower leg press on the Universal Gym in healthy, non-injured male students [94, 95]. Validation of the one RM leg press performance as a measure of lower extremity isotonic strength was established by Jackson, Watkins and Patton (1980) through a factor analysis on twelve isotonic strength
performances. The data revealed that measurements of isotonic strength taken from college-aged males on a Universal Gym can be reduced to upper and lower extremity assessments with the leg press being the most valid measure of lower extremity isotonic strength [95]. In fact, various investigators have since used the one RM leg press as the gold standard in validation studies of other lower limb strength testing protocols [93, 96].

Normative data on college aged males for one RM isotonic leg press ability is available for comparison when assessing isotonic strength on the Universal Gym in similar populations [94, 97]. However, these reference norms will not be used for comparison in this thesis due to the differences in test protocols employed for instance, double versus single-leg press.

Another isotonic muscle function test, the vertical jump, has been used throughout the literature as an indirect measure of leg power as the value of the vertical jump height has proven to be highly correlated to the peak power recorded by a force plate [98].

A modification of this test, the single-leg vertical jump, has been employed in order to compare limb performance within an individual [9]. The test-retest reliability of the single-leg vertical jump has been assessed and the consistency of the vertical height achieved has been established using intra-class correlation coefficients (ICCs) [14, 18, 99]. Using a standardized protocol, the single-leg vertical jump has been proven to be reliable in a healthy non-injured population [14, 18], along with an ACL reconstructed (ACLR) population [99], with ICCs ranging from 0.79 to 0.96. There have been no reliability studies of the single-leg vertical jump within the ACLD population to date.

Overall, the maximum height achieved in the performance of the single-leg vertical jump has demonstrated no significant difference between the dominant and non-dominant limb in a
healthy, non-injured population [9, 99]. In an ACLD population, the single-leg vertical jump height achieved on the injured limb is impaired compared to the non-injured limb [9]. However, Barber, Noyes, Mangine, McCloskey and Hartman (1990) explored the distribution of the vertical jump index for the single-leg vertical jump test in a sample of healthy, non-injured individuals and found a large standard deviation which was not attributable to a particular sports activity group or gender (Table 2). They determined the limb symmetry index for the single-leg vertical jump to be 80% however, 27% of the normal population fell outside of this normal range. Since such a large percentage of healthy, non-injured subjects scored outside of the normal limb symmetry range, Barber et al. (1990) did not recommend the use of the single-leg vertical jump in the detection of lower limb functional limitations [9]. Petschnig, Baron and Albrecht (1998) also explored the specificity of the single-leg vertical jump but found a vertical jump index of 85% or greater in 96% of their 50 healthy, non-injured males [100]. The differences in these investigators’ findings may be attributed to differences in their respective test protocols. Although Petschnig et al.’s (1998) protocol proved to be reliable (0.88) it cannot be compared with that of Barber et al.’s, (1990) since they did not report on the reliability of their test protocol.

For single-leg vertical jump scores and differences in limb performance within healthy, non-injured, ACLD and ACLR populations cited within the literature see Table 2.
Summary of Single-Leg Vertical Jump Scores cited within the Literature

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Participants</th>
<th>Details</th>
<th>Arm Swing</th>
<th>Jump Index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEALTHY, NON-INJURED</td>
<td>Barber et al. (1990)</td>
<td>n=93 healthy, non-injured (35 males and 43 females)</td>
<td>Details not provided</td>
<td>26.9 ±12.2 (D*)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>26.4 ±12.2 (ND*)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The mean of two test trials.</td>
<td>Difference = 0.520 (n/s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Jump Index = 105% ±22</td>
</tr>
<tr>
<td></td>
<td>Bandy et al. (1994)</td>
<td>n=16 healthy, non-injured males</td>
<td>24.0 ±2.78 years</td>
<td>32 ± 6.2 (D)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>31 ± 4.5 (ND)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Arm swing permitted.</td>
<td>Difference = 2% (n/s)</td>
</tr>
<tr>
<td>ACLD</td>
<td>Barber et al. (1990)</td>
<td>n=35 (26 males and 9 females) with a unilateral ACL deficiency</td>
<td>25 years</td>
<td>22.2 ±17.1 (INV*)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Not provided</td>
<td>28.1 ± 8.2 (NON-INV*)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Arm swing permitted.</td>
<td>Difference = 5.90;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The mean of two test trials.</td>
<td>p = 0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Jump Index = 77 ±22%</td>
</tr>
<tr>
<td>ACLR</td>
<td>Brosky et al. (1999)</td>
<td>n=15 physically active males after unilateral ACL reconstruction</td>
<td>26.0 ±7.3 years</td>
<td>39.6 ±6.5 (INV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>28.9 ± 8.9 years</td>
<td>40.6 ± 7.4 (NON-INV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Arm swing permitted.</td>
<td>Difference (n/s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean of all test trials (3 test trials for a total of 5 test sessions)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Summary of the single-leg vertical jump scores and limb differences (p-values) in healthy, non-injured, ACLD and ACLR samples. * D= dominant limb; ND= non-dominant limb; INV= involved limb and NON-INV= non-involved limb. ~n/s= not significantly different.

Assessment of isokinetic muscular function most commonly employs a motorized isokinetic dynamometer. Such devices permit the isolation of weak muscle groups and provide a highly reproducible assessment of dynamic strength by providing an accommodating resistance to muscular torque developed during the course of the contraction to control the angular velocity [88]. The use of microprocessors with isokinetic dynamometers enable the calculation of many muscular function parameters including peak torque (PT), average torque, angle specific torque, work, power, torque acceleration and endurance index [89]. However, isokinetic devices are
expensive, assess movements that are 'unnatural' to the human body in that the angular velocity is held constant throughout the range of motion of the joint and may produce large loads on the joint being tested [89, 91].

There are a number of different isokinetic dynamometer devices available and although it is possible to acquire accurate and reliable measures of strength (PT) from these devices, investigators should not assume that all are accurate and reliable [91].

Validity and reliability studies have proven that the Lido Active dynamometer is valid and reliable for velocity and torque measurements. Patterson and Spivey (1992) used instrumentation with established technical accuracy (camcorder, video-cassette recorder, customized wheel attachment and four known calibrated weights) and applied known forces to the actuator of the isokinetic device at 5°s⁻¹ and repeated this test on two occasions, one week apart. The Lido Active was deemed to be valid (r=0.98) and reliable (r=1.00) with respect to torque measurements within their specific testing parameters [101]. Brown, Whitehurst and Bryant (1992) provided further confirmation of the reliability of the Lido Active Dynamometer in a test-retest assessment of the concentric mode. Through an assessment of the knee flexors and extensors on two occasions, two days apart, Brown et al. (1992) determined PT, average work and average power to be reliable (r=0.90-0.99) at 60, 180, 300 and 400 °s⁻¹ [102].

Studies conducted to compare normative data using different (reliable) isokinetic systems have determined that assessment results are dynamometer specific [89, 103, 104]. For instance, Cress, Johnson and Agre (1991) compared PT and work of knee flexion and extension at four different angular velocities using the Lido Active and Lido Digital isokinetic systems in 25 older healthy women and demonstrated significantly different results [104]. Therefore, although isokinetic devices may have demonstrated adequate validity and reliability, caution should be
taken when comparing results across isokinetic systems or when comparing patients' results with norms if data is obtained on different systems. In fact, data should be gathered on the same system in order to produce comparable results [103, 104].

Normative PT knee flexion and extension values using the Lido Active system have been reported by Lord, Aitkens, McCrory and Bernauer (1992). Mean PT of knee extension and flexion was 190Nm and 109 Nm at 60°s\(^{-1}\), 163Nm and 95Nm at 120°s\(^{-1}\) and 136Nm and 85Nm at 180°s\(^{-1}\) for 20 healthy subjects (eleven male and nine female) between 20 to 39 years [88]. Since the investigators combined gender scores this normative data will provide minimal insight into how the Controls and ACLD subjects in the present study perform in comparison.

### 2.6.4 Fear of Subluxation on Landing

A profile of ACLD individuals demonstrated that a subluxation of the knee is most likely to occur at footstrike (or shortly after) during activities involving sudden changes in direction, quick stops and jumping movements [58]. Hence, the fear of subluxation on landing has been considered a possible cause in the reduction of the distance jumped in the OLHD in the ACLD population [105, 106]. To date, the impact of the psychological factor of fear of subluxation in landing has not been assessed in relation to OLHD performance in the ACLD population.

According to Bandura (1982), self-efficacy is an individual’s perception of their capabilities (or self-confidence) within a particular domain of activities and one’s perceptions will either hinder or facilitate an individual’s decision to engage in a particular activity. In the assessment of self-efficacy, Bandura cautioned that perceived self-efficacy will vary across activities and situational circumstances thus, the measurement of self-efficacy should be activity/situation specific [107]. Modeled after Bandura's self-efficacy framework, a fear of subluxing on landing operationalized into a confidence continuum to quantify the psychological component of landing the OLHD on
an ACLD knee was proposed in this thesis using a single item, 0 to 100% response continuum. A continuous (0 to 100%) versus dichotomous format ("Yes"/"No") was employed as a multiple response measure is more reliable and has greater utility as an evaluative tool than a dichotomous measure [108, 109]. See Section 4.2.2.4 for more details of the confidence in landing scale proposed.

2.6.5 The IKDC Knee Ligament Standard Evaluation

The International Knee Documentation Committee, founded in 1987 by a group of knee surgeons from Europe and the United States, agreed on a common terminology and created a standard knee ligament evaluation form which has gained widespread acceptance since its inception [110].

The overall purpose of this concise one-page evaluation is to compare treatment methods therefore, it is often used pre- and post-operatively and at follow-up [110]. There are eight groups of assessments including patient subjective assessment, symptoms, range of motion (ROM), stability, crepitus, harvest sight pathology, X-ray findings and a functional test (OLHD). However, only the first four groups count toward the final grade and are supplemented by the remaining four areas [110]. The lowest grade within a group determines the group grade and the worse group grade determines the overall score. The four grades are "Normal" (A), "Nearly Normal" (B), "Abnormal" (C) and "Severely Abnormal" (D) [110].

Johnson, Ryan and Smith (2000) evaluated the reliability of the IKDC by assessing 102 patients using a single examiner. The initial examiner reassessed 47 of these patients and a second examiner performed a repeat assessment on a total of 35 of the patients. They found that when the separate items were used the reliability fell below acceptable levels especially for knee ROM and ligamentous laxity examination findings [111]. Details including the time frames between
test sessions, experience of the examiners and the method of data analysis were not reported within this abstract, making its critical appraisal difficult.

The use of the IKDC evaluation form may reveal less-favorable results than those evaluated with other current knee scoring scales as a persistent knee problem cannot be concealed with a high numerical score added for other, non-related, parameters [110, 112]. However, knee-rating systems that are partially based on joint laxity measures, such as the IKDC standard knee evaluation form, may overestimate the disability after ACL injury [112, 113]. For instance, Synder-Mackler, Fitzgerald, Bartolozzi and Ciccotti (1997) found no difference in the overall IKDC grade between ten ACLD patients who were classified as "copers" (able to return to all sporting activities) versus ten "non-copers" (required surgical reconstruction despite conservation intervention). In fact, all subjects in the copers group had IKDC ratings of C (abnormal) or D (severely abnormal) [113].

Studies on the relationship and the contribution of the individual groups of the IKDC to the final grade have been conducted. Risberg, Holm, Steen and Beynon (1999) demonstrated that measures similar to those of the IKDC group one to four reflect two to three different aspects of knee function using a factor analysis. Therefore, the investigators stressed the necessity of not combining the individual groups to calculate a final score. On the contrary, Irrang, Ho, Harner and Fu (1998) concluded that all groups (one to four) contribute significantly to the prediction of the IKDC final grade using a stepwise regression analysis [112]. Though, it is not surprising that the group grades one to four predict the final IKDC grade as determined by way of a stepwise regression analysis since the final grade is based on one of the grades from group one to four of the IKDC. Moreover, conducting a stepwise regression analysis on such ordinal data should be performed cautiously [114].
The criterion validity of the IKDC groups one to four was evaluated by Risberg et al. (1999) by relating each group to a comparable outcome measure frequently used within the literature. Group one (patient subjective assessment) was compared to a visual analog scale (VAS), group two (symptoms) to the Cincinnati knee score, group three (ROM) to goniometer measurement and group four (ligamentous laxity) to the KT 1000. The IKDC groups one to four demonstrated a high criterion validity implying that the IKDC 1 to 4 is a good means of documenting clinical examination at one follow-up post ACL reconstruction [114].

Sensitivity of the IKDC (groups one to four and the final grade) to changes over time post ACL reconstruction was also investigated by Risberg et al. (1999) by completing the standard knee evaluation at three, six, 12 and 24 months post ACL reconstruction in 120 patients. Results revealed that the IKDC group one, two and the final grade were not sensitive to change over time [114].

2.7 FUNCTIONAL LIMITATIONS

In the NCMRR model, the term 'functional limitation' implies a restriction or lack of ability to perform an action in the manner consistent with the purpose of an organ or organ system [73]. In an attempt to quantify function in the athletic ACLD population, clinicians and researchers have designed various functional performance tests which simulate the stresses about the knee encountered during sporting activities [4, 8]. The OLHD is one of the most commonly employed tests of function in the ACLD population. The focus of this section will be on the scoring of the OLHD, test re-test reliability as well as sensitivity and specificity in the detection of ACL injuries. In addition, a subjective evaluation of symptoms and function, the Modified Knee Scoring Scale of Lysholm, will be discussed.
2.7.1 One-Leg Hop for Distance (OLHD)

2.7.1.1 Description

Daniel, Malcom, Stone, Perth, Morgan and Riehl first introduced the OLHD in 1982 [105] and its use has become widespread, especially since its inclusion in the IKDC standard knee ligament evaluation. A thorough review of the literature using the following databases: Medline, Cinahl, Embase, Sports Discus and Science Citation Index, revealed that the OLHD has been cited as an independent assessment tool of lower extremity function in 147 articles. This test of lower limb function is a relevant task to assess since injury to the ACL occurs in young athletic adults and their functional limitations are most evident during the performance of challenging athletic activities. In addition to being a relevant task to assess, the OLHD is practical in that it can be conducted in any clinical setting and requires minimal staff training, time and equipment [9-13].

The OLHD is most often performed in accordance with the descriptions provided originally by Daniel et al. (1982), where the subject is required to stand on one-limb, hop as far forward as possible, and land on the same limb. The distance is recorded with a tape measure, which is fixed to the ground. Each limb is tested three times, alternating between limbs [105].

2.7.1.2 Scoring the OLHD

2.7.1.2.1 Hop Distance

Measurements of the OLHD include the hop distance (centimeters or meters) and the hop index (ratio or percentage of limb performance). In the ACLD population, the hop distance is reported in terms of their injured and non-injured limb. Whereas in a healthy population, it has been reported in terms of the non-dominant and dominant limb distance [9], the lesser versus greater [105], as well as the left versus the right [115]. Throughout the literature, the hop distance has been reported either as the mean or the longest of three hop trials [105, 115-118]. However, it has been demonstrated that these two different strategies result in significantly different hop
distance scores therefore, the clinician or researcher must be mindful of the strategy used if comparing hop distance results [12].

Many authors have reported on the test re-test reliability of the hop distance scores to establish the consistency and dependability of the measurements using intra-class correlation coefficients (ICCs) [11, 12, 14-18, 99]. Using a standardized protocol, the OLHD has been proven to be highly reliable in a healthy non-injured population [11, 14-18] and an ACLR population [11, 12, 15], with ICCs ranging from 0.79 to 0.99 and 0.88 to 0.96, respectively (Table 3). Upon review of the literature, there have been no reliability studies of the OLHD within the ACLD population to date.
Summary of the Test Re-test Reliability of the OLHD cited within the Literature

<table>
<thead>
<tr>
<th>REFERENCE</th>
<th>SUBJECTS</th>
<th>TEST PROTOCOL</th>
<th>MEASUREMENTS</th>
<th>ICC</th>
<th>HEALTHY, NON-INJURED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hu et al. (1992)</td>
<td>Healthy, n=30</td>
<td>-OLHD &amp; single-leg vertical jump w/o use of arms</td>
<td>-2 test days, 7 days apart; -16 randomized trials per visit</td>
<td>0.79 to 0.96</td>
<td></td>
</tr>
<tr>
<td>Bocher et al. (1993)</td>
<td>Healthy, n=18 (4 male; 14 female)</td>
<td>-OLHD and 2 other functional tests</td>
<td>-2 test days, 1 day apart; -1 practice / 2 test trial each limb</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Bandy et al. (1994)</td>
<td>Healthy, n=18 (all male)</td>
<td>-OLHD w use of arms</td>
<td>-3 test days, 7 days apart; -2 practice/2 test trials each limb 1st test day &amp; dominant limb only 2nd &amp; 3rd test day</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td>Bolga et al. (1997)</td>
<td>Healthy, n=20 (5 male; 15 female)</td>
<td>-OLHD and 3 other functional tests</td>
<td>-2 test days, 2 days apart; -3 practice/3 test trials on dominant limb</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>Ageber et al. (1998)</td>
<td>Healthy, n=75 (36 male; 39 female)</td>
<td>-OLHD w arm use</td>
<td>-2 test days, 7 days apart; -3 test trials</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>ACLR &amp; HEALTHY, NON-INJURED</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Paterno et al. (1996)</td>
<td>ACLR, n=13 (8 male; 3 female)</td>
<td>-OLHD w/o use of arms</td>
<td>-2 test days, 1 day apart; -3 practice/3 test hops</td>
<td>ACLR: 0.89 (INV* &amp; NON-INV*)</td>
<td></td>
</tr>
<tr>
<td>Kramer et al. (1992)</td>
<td>ACLR, n=38 (22 male; 16 female)</td>
<td>-OLHD w use of arms</td>
<td>-2 test days, 5 days apart; -several practice / 3 test trials alternating limbs</td>
<td>0.92 (INV); 0.91 (NON-INV)</td>
<td></td>
</tr>
<tr>
<td>Brosky et al. (1999)</td>
<td>ACLR, n=15 (all males)</td>
<td>-OLHD, single-leg vertical jump &amp; timed hop w arm use</td>
<td>-5 test days, all tests performed within 2 wks; -1 practice (initial test day only) / 3 test trials alternating limbs</td>
<td>0.88 to 0.97 (INV &amp; NON-INV within and between trials for the 3 functional hop tests)</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Summary of the ICCs reported in the literature on the test re-test reliabilities of the OLHD. *INV= involved limb; *NON-INN= non-involved limb; *D= dominant limb and *ND= non-dominant limb.
Some authors have explored the difference between the hop distance scores, within and between test sessions, to determine if there is a learning effect associated with performing the OLHD. Bolgla and Keskula (1997) had subjects perform three test trials of the OLHD on the dominant limb only on two separate test days, two days apart. They reported significant differences in hop distance scores that were attributed to the differences found between the first and last hop trials over the two test days. However, the actual percent difference of the average hop distances between the two test days was less than 2%. This finding is consistent with that of Kramer, Nusca, Fowler and Webster-Bogaert (1994), who reported that the percent difference between the scores determined on two different test days averaged only 3%. Consequently, any learning effect associated with performing the OLHD is minimal and data gathered on one test occasion are reliable and can be used comparatively [12].

In a non-injured, healthy population, distance hopped is not affected by leg dominance [9, 14]. In an ACLD population, hop distance is reduced on the injured limb but the effect of leg dominance is unknown [9, 106, 115, 116, 118, 119]. Table 4 summarizes hop distance scores for males, for comparison with the current study populations [12, 52, 120-122].
### Summary of Hop Distance Scores (OLHD) cited within the Literature

<table>
<thead>
<tr>
<th>Reference</th>
<th>Subject Description</th>
<th>Arm swing permitted?</th>
<th>Measurements and Test Trials</th>
<th>Non-Dominant Limb</th>
<th>Notes</th>
<th>Dominant Limb</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HEALTHY NON-INJURED MALES</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Barber et al. (1990)</td>
<td>Sports participation level: I: 4-7 times wk’ (n=18) II: 1-3 times wk’ (n=17) III: elite soccer (n=15)</td>
<td>Details not provided</td>
<td>N/A</td>
<td>Arm swing permitted. The mean of two test trials.</td>
<td></td>
<td>187.8 ±25.5 (D*) 189.6 ±27.6 (ND*) (n/s~)</td>
<td>149.6 ±17.3 (D) 150.7 ±16.2 (ND) (n/s) 204.0 ±14.9 (D) 202.3 ±9.8 (ND) (n/s)</td>
</tr>
<tr>
<td>Bandy et al. (1994)</td>
<td>n=18</td>
<td>25.2 ±3.6 years</td>
<td>N/A</td>
<td>Arm swing permitted. The best of two trials.</td>
<td></td>
<td>204.5 ±90.17 (D) 204.7 ±96.8 (ND) (n/s)</td>
<td></td>
</tr>
<tr>
<td><strong>ACLD MALES &amp; HEALTHY, NON-INJURED MALES</strong></td>
<td></td>
<td></td>
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<tr>
<td>Tegner et al. (1986)</td>
<td>ACLD: n=26 All but 2 were competitive athletes (16 had associated medial instability and 11 had undergone a meniscectomy) CONTROLS: n=66 amateur soccer players</td>
<td>27 ±6 years</td>
<td>Details not provided</td>
<td>Hands behind the back. The best of 3 trials.</td>
<td></td>
<td>145 ±26 (INV*)</td>
<td>177 ±14 (p&lt;0.001)</td>
</tr>
<tr>
<td><strong>ACLD MALES</strong></td>
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</tr>
<tr>
<td>Gauffin, Pettersson &amp; Tropp (1990)</td>
<td>n=16 All meniscal lesions had been repaired arthroscopically.</td>
<td>30 ±8 years</td>
<td>58.8 ± 3.2 months</td>
<td>Hands behind the back. The best of 3 trials.</td>
<td></td>
<td>155 ±20 (INV) 163 ±18 (NON-INV*) (p=0.01)</td>
<td></td>
</tr>
<tr>
<td>Gauffin, Pettersson, Tegner &amp; Tropp (1990)</td>
<td>n=15 No collateral ligament laxity or meniscal symptoms</td>
<td>27 ±3 years</td>
<td>16 ±9 months</td>
<td>Hands behind the back. The best of 3 trials.</td>
<td></td>
<td>157± 16 (INV) 164± 13 (NON-INV) (p&lt;0.05)</td>
<td></td>
</tr>
<tr>
<td>Gauffin &amp; Tropp (1992)</td>
<td>n=9 Meniscal lesions repaired 12 months post injury. A good Lysholm score (&gt;90) was required.</td>
<td>29 ±4 years</td>
<td>63 ± 32 months</td>
<td>Hands behind the back. The best of 3 trials.</td>
<td></td>
<td>161 ± 13 (INV) 173 ± 18 (NON-INV) (p=0.01)</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4** Summary of the hop distance scores and limb differences (p-values) in healthy, non-injured and ACLD males

* D= dominant limb; *ND= non-dominant limb; *INV= involved limb; *NON-INV= non-involved limb and ~n/s= not significantly different
2.7.1.2.2 **Hop Index**

The hop index is more commonly utilized than the hop distance within the clinical setting as it can provide a more meaningful outcome of performance on an individual basis since the non-involved limb can serve as a means for comparison.

The hop index expresses the hop distance achieved on one limb relative to the other. In the ACLD population, the hop distance achieved on the injured limb is expressed relative to that of the non-injured limb. In a healthy population, the hop index has been expressed as: the hop distance achieved on the non-dominant relative to that of the dominant limb [9]; the lesser hop distance relative to the greater [105] as well as the hop distance achieved on the left relative to the right [115].

Different methods in computing the hop index have been employed including taking an average of three hop trials or selecting the longest hop. Either method may be used as it has been demonstrated that the hop index is unaffected by the two different data analysis strategies [12].

The effect of gender, athletic participation and leg dominance on hop index scores has been investigated in healthy, non-injured individuals [9, 105, 115]. Daniel et al. (1982) assessed the effect of gender on the lesser/greater limb ratio and found that the females demonstrated more asymmetry [105]. However, subsequent work by Daniel et al. (1988) classified subjects with respect to activity level and gender and found no significant athletic participation or gender effect on the left/right limb ratio [115]. Similarly Barber et al. (1990) demonstrated no significant difference in hop index as related to gender, sports activity level or leg dominance [9].

Reference norms have been put forth by each group of investigators based on the specific findings of their respective studies. Daniel et al. (1982) specified different reference norms for males versus females whereas, Daniel, Stone, Riehl and Moore (1988) and Barber et al. (1990)
combined all subjects in order to determine reference norms [9, 105, 115]. See Figure 4 for the distribution of the hop indexes within healthy, non-injured individuals and Table 5 for the corresponding hop index reference norms that have been cited within the literature.

Distribution of the Hop Indexes in Healthy, Non-injured Subjects cited within the Literature

Figure 4  Summary of the distribution of the hop indexes in healthy, non-injured subjects cited within the literature. Daniel et al. (1988) demonstrated that 95% scored a hop index \( \geq 90\% \) and the remaining 5% scored between 85 and 90% [115]. Daniel et al. (1982) demonstrated 95% of the male subjects scored a hop index \( \geq 90\% \) (hop index scores of the remaining 5% was not reported) [105]. Lastly, Barber et al. (1990) demonstrated 93% scored a hop index \( \geq 85\% \), 3% scored below 85% and 4% scored above 100% [9].
Table 5 Summary of Hop Index Reference Norms cited within the literature.

Possible explanations for the differences found in the documented hop index reference norms may include: 1) the analysis of sub-populations individually versus collectively, for example males and females; and/or 2) utilizing different strategies to calculate the hop index ratio for instance, lesser/greater, left/right and non-dominant/dominant.

The studies cited in Table 5 did not use the same sub-population (males) plus the same method to calculate the hop index (non-dominant/dominant) as the present study. Therefore, both the 85% and 90% hop index reference norms established by Barber et al. (1990) and Daniel et al. (1982 and 1988) respectively will be referred to throughout this thesis [9, 105, 115]. See Table 6 for hop index scores within healthy, non-injured and ACLD populations (including males and females) cited within the literature.
### Summary of Hop Index Scores cited within the Literature

<table>
<thead>
<tr>
<th>Reference</th>
<th>Subject Description</th>
<th>Age Range (years)</th>
<th>Follow-up (months)</th>
<th>Arm Swing Permitted. The Mean of Three Test Trials</th>
<th>Test Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HEALTHY, NON-INJURED</strong></td>
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<tr>
<td>Daniel et al. (1988)</td>
<td>n=100 (63 males &amp; 37 females)</td>
<td>15-45</td>
<td>N/A</td>
<td></td>
<td>99%</td>
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<tr>
<td><strong>HEALTHY, NON-INJURED AND ACLD</strong></td>
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<tr>
<td>Tegner et al. (1986)</td>
<td>CONTROLS: n=66 male amateur soccer players</td>
<td>23 ±5 years</td>
<td>N/A</td>
<td>Hands behind the back. The best of 3 trials.</td>
<td>96 ±3%</td>
</tr>
<tr>
<td></td>
<td>ACLD: n=26 males</td>
<td>27 ±6 years</td>
<td>Details not provided</td>
<td></td>
<td>ACLD: 90 ±11% (p&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td>All but 2 were competitive athletes (16 had associated medial instability and 11 had undergone a meniscectomy)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barber et al. (1990)</td>
<td>CONTROLS: n=93 (50 males &amp; 43 females)</td>
<td>Details not provided</td>
<td>N/A</td>
<td>Arm swing permitted. The mean of two test trials.</td>
<td>100 ±13%</td>
</tr>
<tr>
<td></td>
<td>ACLD: n=35 (26 males &amp; 9 females)</td>
<td></td>
<td></td>
<td></td>
<td>ACLD: 82 ±17% (p value not provided)</td>
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<tr>
<td><strong>ACLD</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Gauffin, Patteasson &amp; Tropp (1990)</td>
<td>n=16 males All meniscal lesions had been repaired arthroscopically.</td>
<td>30±8 years</td>
<td>58.8 ±3.2 months</td>
<td>Hands behind the back. The best of 3 trials</td>
<td>95 ±6%</td>
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</tr>
<tr>
<td>Gauffin &amp; Tropp (1992)</td>
<td>n=9 males Meniscal lesions repaired 12 months post injury. A good Lysholm score (&gt;90) was required.</td>
<td>29±4 years</td>
<td>63 ±32 months</td>
<td>Hands behind the back. The best of 3 trials</td>
<td>93 ±7%</td>
</tr>
</tbody>
</table>

**Table 6** Summary of the hop index scores cited within the literature.

To determine the ability of the hop index to detect lower limb functional limitations in individuals with an ACLD knee the sensitivity, specificity, false negative and false positive rates have been investigated [9, 13]. The results demonstrate: a low probability of yielding abnormal results in an ACLD knee (low sensitivity); a high probability of demonstrating a normal hop index in a
normal knee (high specificity); a high probability of demonstrating a normal hop index in an ACLD knee (high false-negative); and a low probability of demonstrating a an abnormal hop index in a normal knee (low false positive) (Table 7). The low sensitivity rate lead investigators to conclude that the OLHD can not be used to detect functional limitations attributed to an ACL injury [9, 13].

**Sensitivity and Specificity of the Hop Index in the Assessment of ACL Injuries: Results are % of study populations: Noyes et al. (1991) and Barber et al. (1990) [9, 13]**

<table>
<thead>
<tr>
<th></th>
<th>ACLD</th>
<th>Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abnormal Hop Index</td>
<td>52%; 51%</td>
<td>3%; 3%</td>
</tr>
<tr>
<td>(&lt;=85%*)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal Hop Index</td>
<td>48%; 49%</td>
<td>97%; 97%</td>
</tr>
<tr>
<td>(&gt;=85%*)</td>
<td></td>
<td></td>
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</tbody>
</table>

Table 7 Summary of the % of tests that yielded an abnormal hop index in the ACLD (sensitivity); a normal hop index in normal knees (specificity); a normal hop index in the ACLD (false-negative) and an abnormal hop index in normal knees (false-positive).

*Barber et al. (1990) hop index reference norm was utilized in both studies [9].

However, these sensitivity studies did not consider the limitations associated with the diagnostic accuracy of the hop index including: 1) the differences in inherent athletic ability and; 2) the differences in leg dominance when comparing the ACLD knee to an uninjured knee (for both within and between patient comparisons). Therefore, the impact that these two sources of error on the sensitivity of the OLHD in the assessment of ACL injuries is unknown.
2.7.2 Modified Knee Scoring Scale of Lysholm & Tegner Activity Scale

In 1985, Tegner and Lysholm modified the Lysholm scale (developed in 1982) to better reflect symptomatology and functional limitations in ACLD individuals with concomitant meniscal pathology [123]. This knee scoring scale has been one of the most widely used in the evaluation of ACL injury and reconstruction. In fact, Hoher et al. (1997) found 106 publications, which employed the use of this knee scoring scale [114]. Tegner and Lysholm also introduced an activity grading scale in 1985 as a complement to the functional score since limitations in the individual’s knee function may be masked or exacerbated by the level of work and/or athletic participation [123].

The Modified Knee Scoring Scale of Lysholm is comprised of eight subcriteria (three functional and five subjective). The summation of scores from the eight subcriteria provides an overall score from 0 to 100. A maximum score of 100 implies the absence of: a limp (five points), use of support (five points), locking (15 points), feelings of instability (25 points), pain (25 points) and swelling (ten points) and no problems with stair climbing (ten points) or squatting (five points) [123]. However, there was no explanation given regarding the allocation of points to the various subcriteria by the authors. The authors interpretation of the overall score is as follows: ‘excellent’ (95-100), ‘good’ (84-94), ‘fair’ (65-83), or ‘poor’ (<64) [123] once again, no rationale was provided.

Tegner and Lysholm (1985) explored the intra-rater reliability of the Modified Knee Scoring Scale of Lysholm by having an orthopaedic surgeon administer the scale on two different occasions, two weeks apart, to 15 ACLD patients. In addition, they assessed the inter-rater reliability by letting the same orthopaedic surgeon and a physical therapist determine the score for the same 15 ACLD patients on one occasion (same day). They demonstrated intra and inter-rater test-retest correlation coefficients of 0.97 and 0.90, respectively [123].
Mollborg and Werner (1996) also assessed the reliability of the Modified Knee Scoring Scale of Lysholm in 31 patients with one of four diagnoses (ACL injury, meniscal tear, patello-femoral pain syndrome or lateral ankle sprain) on three different occasions (day one, three and 14) via telephone interviews. The correlation between the scores from days one to three was 0.75, days one and 14, 0.69 and days three and 14, 0.68 [125]. These results do not reflect the high degree of reliability as demonstrated by Tegner and Lysholm (1985). However, Bengtsson et al. (1996) failed to report on the reliability of the score for the four different groups separately in addition, they neglected to mention the number of interviewers involved. Both of these factors would impact the reliability of the knee scoring scale.

The validity of the original Lysholm score was verified by its authors upon demonstrating that patients with objective knee instability scored significantly lower than patients with minimal or no objective instability (mean score 75.6 ±17.8 and 93.6 ± 10.9, respectively, p<0.001) [124]. However, the validity of the Modified Knee Scoring Scale of Lysholm in the assessment of patients with ACL injuries has been challenged since. Bengtsson et al. (1996) assessed the sensitivity of this knee scoring scale in individuals, with one of four different diagnoses, beyond the acute (<1month) stage of their injury. These investigators found the sensitivity of the Modified Knee Scoring Scale of Lysholm was better for patients with meniscus injury (mean score=62.3), patellofemoral pain syndrome (73.4), and lateral ankle sprain (64.6) than for those with an ACL injury (81.1) [125]. This suggests that the Modified Knee Scoring Scale of Lysholm is not sensitive to symptoms or functional limitations consequential to injury to the ACL.

Moreover, upon following 120 ACLR patients at three, six, 12 and 24 months post operatively, Risberg et al. (1999) found the original Lysholm scoring scale to be sensitive to clinical change from the three to six month follow-up only. Whereas, the Cincinnati knee score demonstrated a significantly improved outcome between each of the follow-up time periods. Consequently,
Risberg et al. (1999) deemed the original Lysholm scale not sensitive to change over time and therefore not an appropriate outcome after ACL reconstruction [114].

The Tegner Activity Scale is a numerical rating system, which defines ten categories of functional status related to sport and work performance. Scores range from ten to zero, with ten representing participation in competitive elite sporting activities and zero representing no activity secondary to the knee condition. Activity levels five through ten can be achieved only if the patient takes part in recreational or competitive sports [123]. The measurement properties of this activity scale (reliability and validity) have not been adequately assessed to date.

2.8 PERCEIVED DISABILITY

In the NCMRR model, the term "disability" refers to a limitation or inability in performing tasks, activities, and roles to levels expected within physical and social contexts [73]. Various scoring systems have been proposed to assess disability post knee injury however, many are not self administered and combine assessments of symptoms, clinical findings and function [126]. In order to obtain a true reflection of a patient's perceived disability it is important that the assessment is free of examiner bias, provides a comprehensive reflection of the patient's opinion (questions and answer options) in addition to being reliable, responsive to clinical change and valid. [126, 127]. Furthermore, an instrument used to assess perceived disability in the ACLD population should be condition-specific due to the issue of chronicity and the fact that demographically, the ACL injured are younger and more active than other populations [127]. To date, the only self-administered instrument specifically designed to assess the patient's opinion about their ACLD knee and associated problems is the ACL-QOL questionnaire published by Mohtadi in 1998 [127].
2.8.1 **QOL Assessment in ACL Deficiency (ACL-QOL) Questionnaire**

The ACL-QOL questionnaire includes 32 separate items in 31 questions and uses a 100-mm VAS response format. There are five separate items in the subcategory of symptoms and physical complaints, four within the work-related concerns, 12 in the recreational activity and sports participation or competition, six items related to lifestyle and five questions in the social and emotional domain [127].

The ACL-QOL questionnaire has been shown to be reliable and valid [127]. The test-retest reliability of the ACL-QOL questionnaire revealed an overall average error of six percent between responses completed by 25 patients with chronic ACL deficiency on two occasions, two weeks apart [127].

This questionnaire's ability to detect clinical change, content, face and concurrent validity have been addressed. First, the assessment of its responsiveness to clinical change revealed that 21 of 25 patients (84%) had appropriate overall scores on the re-administration of the ACL-QOL questionnaire based on clinical change that had occurred [127]. Second, Spalding, Foggitt, Arvind and Dunleavy (2000) demonstrated a significant improvement in patient's quality of life scores one year post ACL reconstruction (p=0.01) [128].

Content validity was determined by gaining agreement among 20 knee surgeons on whether the item: 1) represents a QOL issue in the ACLD population; 2) is likely to change as a result of either conservative and/or surgical intervention; and 3) can be appropriately responded to using a VAS format [127].
Face validity was derived from interviews with patients with an ACL deficiency and review of the literature. In addition, input from physiotherapists, athletic therapists, sports medicine physicians and surgeons was sought [127].

Finally, construct validity was demonstrated by the questionnaire being able to measure the full spectrum of disease (scores ranged from eight to 99 out of 100). Furthermore, the questionnaire was able to distinguish between those who went on to have reconstructive surgery (average score of 31) versus those who underwent conservative intervention (average score of 79). More specifically, of the 36 ACLD individuals who went on for surgery, only four had an ACL-QOL score greater than 50 of 100, whereas of those of the 14 ACLD individuals that were treated conservatively, only one had a score less than 50 [127].

Currently, normative data and the generalizability of the ACL-QOL questionnaire has yet to be established [127].

2.9 RELATIONSHIPS BETWEEN IMPAIRMENTS (MUSCULAR FUNCTION AND CONFIDENCE IN LANDING), PERCEIVED DISABILITY (ACL-QOL QUESTIONNAIRE) AND OLHD PERFORMANCE

Studies, which have investigated the relationship between muscular function and OLHD performance, have primarily assessed the knee musculature strength isokinetically via a motorized dynamometer [13, 129-132].

Conflicting results with respect to the degree that isokinetic knee strength correlates to the OLHD prevail throughout the literature. Differences in subject populations, knee pathology, equipment, isokinetic parameters, testing methodology, and analysis of data may have resulted in these inconsistent findings with respect to the relationship between isokinetic strength and OLHD performance [13, 129-132]. Nevertheless, findings with regards to: 1) quadriceps versus
hamstring function; 2) eccentric versus concentric contractions and 3) ACL impaired versus healthy, non-injured individual’s performance provides valuable information regarding the relationship between isokinetic lower extremity strength and OLHD performance.

With respect to the knee musculature, quadriceps versus hamstring strength has been shown to be more highly related to OLHD performance. Studies by Engstrom, Gomitzka, Johansson and Wredmark (1993), Noyes, Barber and Mangine (1991) and Wilk, Romaniello, Soscia, Arrigo and Andrews (1994) investigated the relationship between concentric quadriceps and hamstring isokinetic PT and OLHD performance in ACLD and ACLR populations. Significant correlations were found for concentric quadriceps PT and OLHD performance in all three studies (ranged from r=0.41 to 0.712) whereas, none were reported for the hamstrings [13, 129, 130].

In terms of the type of muscular contraction, the literature suggests that concentric versus eccentric quadriceps strength is more related to OLHD performance. Swarup, Irrgang and Lephart, (1992) correlated both concentric and eccentric quadriceps strength to OLHD performance in a sample of healthy, non-injured individuals. For the males, moderate to strong significant correlations were found for concentric quadriceps PT at 60 and 120° s⁻¹ and the OLHD with and without arm swing (r=0.56-0.72), while no significant correlations for eccentric quadriceps PT and OLHD were found [131]. Similarly, Delitto, Irrgang, Hamer, Fu and Nessi (1993) demonstrated stronger correlations between concentric versus eccentric quadriceps PT and OLHD performance (r=0.382 and r=0.090 respectively) in an ACLR population [132].

The association between isokinetic quadriceps strength and OLHD performance differs between populations [131, 132]. Swarp et al. (1992) investigated the relationship between concentric isokinetic quadricep parameters (PT and work) and OLHD (with or without arm swing) in a healthy, non-injured population [131]. Subsequent work by the same group investigated the
relationship between the same isokinetic parameters and OLHD protocol in an ACLR population. Overall, weaker relationships were found in subjects with knee ligament injuries (r ranging from 0.38 to 0.46) [132] versus those without knee pathology (r ranging from 0.57 to 0.89) [131]. Due to the lower correlation of strength and OLHD performance it would appear that there are other determinants (in addition to isokinetic knee muscular strength) related to the OLHD in the ACLD population.

In terms of isotonic muscle strength, only one study was identified as having investigated the association between a one RM isotonic closed-kinetic chain (squat) test and a long jump performance (r=0.65; p=0.005) which was demonstrated in a sample of 20 healthy, non-injured females [133]. However, comparison of these results to the current study is limited by 1) the differences in the sample studied (healthy, non-injured females only) and 2) the test protocols employed (i.e. bilateral versus single limb assessments).

There were no studies within the literature that explored the relationship between confidence in landing or the single-leg vertical jump test and OLHD performance.

The relationship between perceived disability (ACL-QOL questionnaire) and OLHD performance has been investigated by Spalding et al. (2000) in 60 ACLR patients one-year post surgery [128]. Results demonstrated a poor to moderate correlation between patients’ ACL-QOL score and hop performance (r=0.37; p=0.014). To date, no studies have explored the relationship between perceived disability, as defined by the Mohtadi’s ACL-QOL score, and OLHD performance in the ACLD population.
Summary of Literature Review

Traditionally, the assessment of the ACLD knee has focused on various physical impairments however, their usefulness has been challenged due to lack of a strong relationship with physical function and readiness to return to sports [3-6]. Consequently, orthopaedics has moved toward defining the patients' status by considering the resulting functional limitations and disability that is experienced by the individual.

A commonly employed test in the assessment of knee function in the ACLD population is the OLHD. Using a standardized protocol, this test has been proven to be highly reliable [11, 12, 14-18]. Considerable evidence has demonstrated that ACLD individuals have an impaired hop distance; therefore, the OLHD can differentiate between an ACLD and healthy, non-injured population [106, 115, 116, 118, 119]. However, validity studies pertaining to its diagnostic ability have revealed low sensitivity rates (52 and 51%) thus investigators have concluded that the hop index cannot be used to detect functional limitations in the ACLD on an individual basis [9, 13]. Nevertheless, these studies did not deal with the limitations associated with scoring the OLHD. These include: 1) differences in inherent athletic ability between patients; and 2) differences due to leg dominance when comparing the ACLD knee to an uninjured knee (for both within and between patient comparisons) which will be investigated in the present study.

Mechanisms influencing OLHD performance in the ACLD population have been proposed and include impaired muscular function and a lack of confidence in landing [106]. Strength deficits have been well documented in the ACLD knee [84-87]. To date, investigators have primarily quantified knee muscle function with isokinetic measures. Associations found between isokinetic knee strength and OLHD performance are stronger between quadriceps versus hamstring PT, concentric versus eccentric contractions and in a healthy, non-injured versus ACL impaired population. However, differences in other measures of lower limb muscular
function (including isotonic closed kinetic chain leg extensor strength and leg power indirectly assessed using the single-leg vertical jump) and their associations with OLHD performance have not been investigated. Moreover, the ACLD population’s confidence in landing has never been quantified nor has the relationship between confidence in landing and OLHD performance been assessed.

Finally, there are no published studies that compare an ACLD versus healthy, non-injured populations’ perceived disability assessed by Mohtadi’s ACL-QOL questionnaire. Nor are there any investigations, which correlate this assessment of perceived disability and OLHD performance in the ACLD population.

Therefore, the present investigation provides new insights into the inherent limitations of the diagnostic ability of the hop index scores and into the relationships between OLHD performance, muscular function, confidence in landing and perceived disability in the ACLD.
3.1 BACKGROUND

Injury to the ACL is one of the most common sports-related knee injuries [24]. Rupture of this ligament can be devastating to the athlete due to episodes of giving-way, which are most apparent during demanding sporting activities. Thus, functional tests designed to evaluate knee function in this population attempt to mimic the physiological demands about the knee during athletic endeavors [4, 8]. However, in the realm of lower limb functional tests, no gold standard exists in establishing functional limitations in the ACLD population. Therefore, the test of choice is most often related to the specific functional or athletic requirements of the individual.

One approach in assessing the appropriateness of such lower limb functional tests is to validate the measure for specific applications pertaining to diagnosis, prognosis and responsiveness to treatment [134]. With respect to diagnosis, it is essential that a measure be able to discriminate between individuals, not solely populations, to be considered a useful diagnostic tool.

The OLHD is one of the most commonly employed performance tests utilized in the assessment, prognosis and follow-up of the ACLD patient. This is possibly due to the fact it is considered a relevant task to assess since injury to the ACL usually occurs in young adults with an interest in sports, and most sports demand activities which involve running and jumping. Also, the OLHD is thought to be challenging to the ACLD as subluxation of the knee is most likely to occur at the moment of landing due to the capsuloligamentous sagittal load [24, 106, 119, 135]. Furthermore, it can be conducted in any clinical setting and requires minimal staff training, time and equipment [9-13].
Measurements of the OLHD include the hop distance (centimeters or meters) and the hop index (ratio or percentage of hop distance achieved on one limb relative to the other). The hop index is more commonly utilized within the clinical setting as it provides an easily interpreted outcome on an individual basis. In the ACLD population, the hop index is expressed as the distance achieved on the injured limb relative to that of the non-injured limb. While in a non-injured population, the hop index is typically expressed as the hop distance achieved on the non-dominant relative to that of the dominant limb. Hop index reference norms are used widely as clinical benchmarks for establishing normal versus abnormal OLHD performance [9, 105, 115].

While the reliability of the OLHD has been well established in terms of the consistency of patient scores [11, 12, 14, 136], the validity has not been appropriately assessed concerning the diagnosis of ACL injuries. To date, validity studies of the OLHD in determining its usefulness as a diagnostic tool in detecting lower limb functional limitations in the ACLD population have revealed low sensitivity rates (51-52%) (a hop index ≤85%) [9, 13]. However, these studies did not deal with the inherent limitations associated with the scoring the OLHD, which may affect the sensitivity of this test in its ability to detect lower limb functional limitations in the ACLD population. The two primary limitations associated with scoring the OLHD include: 1) differences in inherent athletic ability; and 2) differences due to leg dominance when comparing the ACLD knee to an uninjured knee (for both within and between patient comparisons).

Comparison of individual hop distance scores is not advised as a result of the differences in hop performance conceivably due to gender, physical anthropometrics and/or athletic ability. Conveniently, the hop index can control for such biologic variability since an individual's opposite limb can be used as a control. However, the hop index is influenced by the magnitude of the underlying hop distance scores. This may affect the sensitivity of the hop index in the detection of lower limb functional limitations when categorizing a hop index as either normal or
abnormal according to the established reference norms. For instance, in the event that two individuals demonstrate a similar absolute difference between limbs, yet achieve different hop distances, the individual who hops farther will receive a higher hop index score.

Differences attributed to leg dominance may also impact the sensitivity of the OLHD scores in the assessment of ACLD injuries. In the ACLD population, the hop distance is reported in terms of their injured and non-injured limb, and the hop index is a ratio of the injured to non-injured limb hop distance performance. Consequently, the impact of leg dominance is not corrected for in either the hop distance or hop index scores which may result in masking or exaggerating functional limitations in the performance of the OLHD when comparing the ACLD knee to an uninjured knee (for both within and between patient comparisons).

Furthermore, there remains great uncertainty regarding the impairments that are most influential in the performance of the OLHD in the ACLD population. Deficits in muscular function and fear of subluxation on landing have been considered creditable causes in the reduction of the distance hopped in the ACLD population [105, 106]. Conclusive evidence regarding the relationship of muscular function to hop performance is lacking and the influence of confidence in landing has not been explored.

As a result of the associated impairments and functional limitations, ACLD individuals are often limited or unable to perform activities or assume roles to levels expected. Instruments (questionnaires) have been developed to gain a better understanding of the ACLD patient's level of perceived disability however, the association between their perception of disability and functional status as defined by the OLHD has not been investigated.
3.2 OBJECTIVES

The objectives of this thesis are as follows:

1) To determine the usefulness of the hop index when used: a) as a descriptive tool in differentiating between ACLD and a healthy, non-injured sample and; b) as a diagnostic tool (i.e., sensitivity and specificity) in the assessment of functional limitations in the ACLD.

2) To determine the impact that controlling for differences in inherent athletic ability and leg dominance has on a) differentiating between ACLD and healthy non-injured sample and; b) the diagnostic ability in the detection of functional limitations in the ACLD.

3) To determine the relationship between muscle function, confidence in landing and OLHD performance in the ACLD and a healthy, non-injured sample and to investigate whether the differences between the ACLD and their matched Controls in muscle function and confidence in landing are related to differences in their OLHD performance.

4) To assess the contributions of take-off (influenced by muscular function) versus landing (affected by fear of subluxation) on OLHD performance.

5) To determine the relationship between OLHD performance and perceived disability and examine whether the differences between ACLD and matched Controls in perceived disability are related to differences in their OLHD performance.
3.3 RESEARCH QUESTIONS

Differentiating between ACLD and healthy, non-injured samples using OLHD scores:

1) Do OLHD scores differentiate between an ACLD and a healthy, non-injured sample?
2) Can the separation between ACLD and Controls in OLHD scores be increased by controlling for differences in inherent athletic ability and leg dominance?

Diagnostic ability of the hop index:

3) Do the established clinical benchmarks for normal versus abnormal limb symmetry (hop index) discriminate between ACLD and Controls?
4) Can the diagnostic ability of the hop index be improved by controlling for differences in inherent athletic ability and leg dominance?

Determinants of OLHD performance:

5) What is the relationship between muscle function, confidence in landing and OLHD performance in the ACLD and matched Controls?
6) What is the relationship between the decline in muscular strength and confidence in landing to the loss in the ability to hop secondary to an ACL injury?
7) What are the contributions of take-off (influenced by muscular function) versus landing (affected by fear of subluxation) on OLHD performance?

Relationship of OLHD performance to perceived disability:

8) What is the relationship between OLHD performance and perceived disability?
9) What is the relationship between an increase in perceived disability to the loss in ability to hop for distance secondary to an ACL injury?
CHAPTER 4
METHODOLOGY

4.1 STUDY DESIGN

This study employed a cross-sectional design to compare OLHD performance, muscular function, confidence in landing and self-perceived disability (ACL-QOL questionnaire) in ACLD patients awaiting reconstructive ACL surgery, with a group of healthy, age and gender matched Controls.

This thesis set out to investigate the difference between ACLD and healthy, non-injured Controls in OLHD scores and the diagnostic ability of the hop index in the assessment of functional limitations in the ACLD. The impact of controlling for differences in inherent athletic ability and leg dominance are explored in attempt to increase the separation of OLHD scores between the ACLD and Controls and improve the diagnostic ability of the hop index. In addition, this thesis will explore the relationship between specific impairments and perceived disability to OLHD performance in order to foster a better understanding of determinants of OLHD performance and provide insight into the relationship between lower limb functional performance and perceived disability in the ACLD.

The Control group serves four purposes within the context of this thesis. First, it serves to provide a reference group in order to determine the difference between ACLD and healthy non-injured subjects in OLHD performance. Second, it serves to control for differences in hop distance scores due to natural variation as a result of athletic ability. Third, it serves to control for the impact of leg dominance on measurement of OLHD scores. Finally, the Controls provide a reference group in order to determine differences between ACLD and healthy Controls in
muscular function, confidence in landing and perceived disability relative to the differences found between the groups' OLHD hop indexes.

Retrospective matching of ACLD and Controls was employed to explore the impact that controlling for inherent athletic ability and leg dominance has on the OLHD scores and the diagnostic ability of the hop index. The matched pairs were subsequently used to compare the variation in measures of muscular function, confidence in landing and perceived disability relative to the variation found in hop index. Explanation of the rationale for the study design and methods follows.

4.2 STUDY DESIGN RATIONALE AND METHODS

4.2.1 Subjects and Subject Recruitment

In order to assess whether the critical measures discriminate between the ACLD and Controls, and to avoid introducing possible confounding factors, subjects were gender- and age-matched.

Male subjects were included only in this study due to: 1) the greater number of males that underwent ACL reconstructive surgery (males: females = 131:80) from 1998 to 1999 (the year prior to data collection) at the Orthopaedic & Arthritic Institute (O&AI) and; 2) the known biomechanical, anatomic and physiological differences between males and females specifically pertaining to strength and function [12, 52, 120-122].

The majority of ACLD individuals seeking reconstructive surgery are young (early 20's to late 30's) active adults. The ACLD and Controls ranged in age from 18 to 42 years and 24 to 35 years, respectively. Muscle strength is maintained or only modestly reduced in the fourth decade [91, 120, 121] therefore, subjects in this study were likely to have experienced minimal age-related changes in muscular function.
Ten male, consecutive consenting ACLD patients of the Orthopaedic and Arthritic Institute (O&AI) were recruited as part of another study. Each ACLD subject was scheduled to undergo ACL reconstructive surgery. Screening methods of the ACLD patients included physicians approval, a medical chart review (including the IKDC standard knee evaluation form) and telephone or one-on-one interview. Eligibility was determined according to a set of inclusion/exclusion criterion (Appendix 1). Ten male, non-injured healthy Controls were recruited from the community through the use of flyers and word-of-mouth. The Control group were deemed eligible upon screening either by telephone or one-on-one interview according to the inclusion and exclusion criteria outlined in Appendix 1.

All participants were educated on the purpose of the study, testing procedures and potential risks. Written consent, in a form approved by the O&AI and the University of Toronto's Ethics Review Committee was obtained from each subject prior to testing (Appendix 2). Subjects were tested on one occasion only and all testing was conducted at the O&AI.

4.2.2 STUDY MEASURES

4.2.2.1 Subject Descriptive Measures

4.2.2.1.1 Knee Scoring Scales

Commonly used rating systems for knee ligament injuries, the Modified Knee Scoring Scale of Lysholm and the Tegner Activity Score [123], were employed primarily for descriptive purposes. Inclusion of these scales permitted a comparison of knee symptomatology, functional limitations and activity levels between the ACLD patients and Controls, in addition to published results.

The Modified Knee Scoring Scale of Lysholm [123] was administered to all subjects (see Section 2.7.2 for description). The most applicable descriptor regarding each of the following: presence of a limp, use of support, locking, feelings of instability, pain, swelling, stair climbing
and squat ability, was selected by the subject. The scores for each of these eight subcriteria were then summed.

The Tegner Activity Score was completed by all subjects [123] (see Section 2.7.2 for description). Each subject chose one of the ten categories of functional status that best reflected their current sport and work performance. The ACLD subjects also chose the functional category that reflected their sport and work performance level prior to their knee injury.

Each of the ACLD subjects had previously undergone (between three and 28 days prior) the IKDC Knee Ligament Standard Evaluation [137] as part of a larger study. Of the various subcategories of this evaluation, ligamentous stability and hop distance scores (of the OLHD) in addition to the overall knee profile score (see Section 2.6.5 for description) were highlighted in this thesis for the following reasons. The degree of ligamentous stability assisted in further defining the ACLD sample within this study. The hop distance scores were used to validate the method of obtaining OLHD scores using the Peak Performance Motion Analysis System in this study. Finally, the overall knee profile score, based on the lowest grade scored for all the subcategories, was used to compare the ACLD subject's knee profiles to other published results.

4.2.2.1.2 Anthropometric Measures

Anthropometric measures were gathered to determine the comparability of the ACLD and Control group with respect to height, BWt, BMI, waist girth, average leg length, percentage of body fat and FFM.
Height was measured to the nearest 0.5 centimeter (cm) using an adjustable measuring stick attached to the Health-o-meter standard beam scale system. Positioning and instruction given was according to the CPAFLA guidelines [74]. BWt was measured to the nearest 0.01 kilogram (kg) on the Health-o-meter standard beam scale system without footwear. BMI was calculated from the height and BWt measures obtained (BWt (height^3)^{-1}). Waist girth was measured to the nearest 0.5 cm according to the CPAFLA guidelines [74]. True leg length was measured to the nearest 0.5 cm from the anterior superior iliac spine to the lateral malleolus with the pelvis level and legs 15 to 20 cm apart [29]. Average leg length was calculated from taking the average of the dominant and non-dominant leg lengths for each subject.

Bio-Impedance Spectroscopy (BIS) determines body composition measures through an analysis of the reactance and resistance of a mild alternating current. The Hydra ECF/ICF (Model 4200) Bio-Impedance Spectrum Analyzer (Xitron Technologies Inc., San Diego, CA) and accompanying software was used for this purpose. Subject’s gender, height and BWt were input in order to predict FFM [138]. The percentage of body fat was then calculated using the following equation:  
\[ \% \text{ Body Fat} = \frac{\text{Fat Mass (FM)}}{\text{BWt} \times 100}, \text{ given FM} = \text{BWt} - \text{FFM}. \]

Measurements were taken according to the manufacturer’s instructions. The subject assumed a supine position, with their limbs abducted. Wearing shorts, a T-shirt and no shoe or sock on the right foot, to allow for placement of the electrodes on the dorsal surface of the right hand and foot, the red-voltage detector was placed proximally to the black-current injection connections. Skin was cleaned with alcohol swabs prior to the placement of the electrodes to reduce surface impedance. Subjects rested in a supine position for a minimum of four minutes prior to data collection to ensure that body fluids had stabilized.
4.2.2.2 OLHD

The OLHD allows for an objective and comparative measure of lower limb performance in the assessment of ACL injuries. While the reliability of the OLHD has been established [11, 12, 14-18, 99], the validity has not been appropriately assessed concerning the diagnosis of ACL injuries. This thesis provides a specific methodological framework to assess the diagnostic validity of this field test in the assessment of functional limitations in the ACLD and it explores the relationship between the expected (Controls) versus the observed (ACLD) difference in specific impairments and perceived disability and OLHD performance.

A modified version of Daniel et al.'s (1982) OLHD described by Tegner, Lysholm, Lysholm and Gillquist (1986) was employed in this study [118]. With hands behind the back, to minimize the effect that arm swing has on the distance jumped, subjects were instructed to stand on one limb and hop as far forward as possible and land on the same limb. Subjects were not permitted to place the other foot down upon landing the OLHD however, they were not required to hold their landing position. All subjects performed a total of three hop trials on each limb, then alternated limbs. Rest periods of approximately two minutes were interspersed between hop trials to minimize the effect of fatigue.

Two-dimensional videotaping of subjects OLHD performance was carried out and hop distances achieved were determined using the Peak Performance Motion Measurement System (Peak Performance Technologies, Inc., Version 5.1.3). This motion analysis system uses opto-electronic motion technology to track the movement of lightweight reflective markers placed on the body and assign position coordinates at regular time intervals from video footage. The reflective markers were placed over the following bony prominences: C7 and L5 spinous process, greater trochanter, lateral femoral condyle, lateral malleolus and head of the fifth metatarsal. Prior to filming subjects, a scaling rod of known length was videotaped and used
during the digitizing process to establish a scale factor for the computer (scaling factor: 161.6 pixels per meter). The hop distance was determined by the change in horizontal position of the subject's lateral malleolus or fifth metatarsal (dependent on visibility) from the beginning to final standing position. The longest distance of the three trials for each leg was used for the hop distance and hop index analysis. The hop index (%) was calculated for the Controls by dividing the longest hop distance score for the non-dominant limb, by that of the dominant limb, and multiplying the outcome by 100. Whereas, the hop index (%) for the ACLD was determined by dividing the longest hop distance score for the injured limb, by that of the non-injured limb, and multiplying the result by 100.

Validation of the hop distance scores obtained using the Peak Performance Motion Measurement System was carried out by comparing scores obtained on the same group of subjects using a direct measurement method, 3 to 28 days prior (Appendix 3).

4.2.2.3 Muscle Function Analysis

General thigh muscle atrophy, changes in the quadricep-hamstring relationship in cross-sectional areas of the thigh and strength deficits have been well documented in the ACLD knee [84-87]. These known strength deficits led to the investigation of knee muscular strength to assess the extent in which strength may explain limitations in OLHD performance in the ACLD. Lower extremity muscular function was evaluated by way of three different methods: 1) isokinetic dynamometry; 2) one RM leg press and 3) single-leg vertical jump.

4.2.2.3.1 Isokinetic Concentric Quadriceps Strength

Isokinetic dynamometry offers a reliable and valid measure of isokinetic muscle strength of isolated muscle groups at various angular velocities [101, 102]. A review of the validity, reproducibility and clinical relevance of the various isokinetic parameters found that PT is the
most properly studied isokinetic strength test parameter and is recommended for clinical and research purposes [89]. Therefore, PT was the muscular function parameter chosen for this study.

Functional activities such as jogging, running, and hopping all require angular velocities of the knee at speed in excess of $200^\circ \text{s}^{-1}$ [139] which can be simulated using an isokinetic dynamometer. However, with increasing angular velocity, the PT usually occurs later in the ROM. Consequently, high angular velocities may be problematic since the limb may pass the optimal joint position for muscular performance and the recorded PT may not represent the subject’s maximal torque capacity [89]. Therefore, isokinetic velocities of 60, 120 and $180^\circ \text{s}^{-1}$ were selected.

The performance of a functional activity requires the coordination of various muscle groups. However, the quadriceps and hamstrings directly effect knee joint stability are of utmost concern in the ACLD individual. In view of the fact that: 1) the quadriceps tends to demonstrate greater strength deficits as a result of ACL injury compared to the hamstring muscles [84-87] and 2) concentric quadriceps strength has been demonstrated to have the strongest correlation with OLHD performance [13, 131, 132, 140, 141], concentric quadriceps strength was the isokinetic muscle contraction assessed within this thesis.

Isokinetic concentric quadriceps knee strength (PT) was tested using a computer controlled (IBM compatible) isokinetic dynamometer (Lido Active by Loredan, Inc., Davis, CA). The seat was adjusted to ensure subjects sat with $110^\circ$ of hip flexion and $90^\circ$ of knee flexion. The axis of rotation of the LIDO controller input shaft was aligned with the knee joint axis. The ankle of the test leg was placed and secured in the ankle cuff attached to the LIDO controller
input shaft. The trunk and thigh were then stabilized to minimize any contribution that the more proximal musculature may have in the movement of the more distal segment. The test knee ROM was set at $-20 \pm 2^\circ$ of knee extension and $90 \pm 2^\circ$ of knee flexion. Prior to testing, the LIDO automatically weighs the limb against gravity in order to correct for the gravitational effect on torque. Subjects were given an opportunity to practice the required knee motion at each of the test velocities prior to data collection. For the actual test performance subjects were instructed to “Straighten then bend your knee as hard and fast as possible”. The test involved five repetitions of knee extension and flexion. Testing was then completed on the opposite limb. The best three of five repetitions (with respect to the coefficient of variation) were used in the data analysis.

4.2.2.3.2 One RM Leg Press Ability

The one RM leg press has proven to be a reliable and valid measure of lower extremity isotonic strength [94, 95]. This type of strength testing employs a type of contraction that more closely resembles human functional movement compared to isokinetic testing [89]. Furthermore, the leg press is more specific to the type of training that the ACLD individual would pursue to increase quadriceps strength as there is less anterior shear (ACL stress) associated with this activity compared to weighted leg extensions [130, 142, 143].

One RM Leg press ability was tested using the Universal © Weight Resistance System (Cedar Rapids, Iowa) according to the Certified Fitness Appraiser Resource Manual guidelines [144]. With the knee in $90^\circ$ of flexion, the subject sat with their back against the backrest, arms crossed over their chest, and the foot of the limb being tested on the foot-plate. Subjects were informed that the lift must begin from a motionless start position and were instructed to “Push the foot-plate to straighten your knee but do not lock it, then, slowly lower the Weight with
control." Prior to the actual test subjects were given an opportunity to practice the test motion once with one plate (47 lbs.). The starting weight was approximately 20% below the subject's estimated one RM weight in order to keep the number of repetitions under five to minimize the effect of fatigue. The subject lifted a succession of heavier and heavier weights once each (in 5 lb. increments) until the one RM weight was determined. Up to two minutes was allowed between each leg press to minimize the effect of fatigue. The test was concluded when the subject demonstrated a failure with a load, utilized alternate movement patterns in order to complete the task or refused to continue the test. This protocol was repeated on the opposite limb.

Isokinetic PT and isotonic one RM leg press ability scores were analyzed relative to BWt in an attempt to eliminate the variation due to individual differences in body type [89, 92, 95].

4.2.2.3.3 Single-Leg Vertical Jump

The vertical jump has been used throughout the literature in the estimate of leg power. Test-retest reliability coefficients of the single-leg vertical jump test are moderate to high (0.79 to 0.96) [14, 18, 99] and the validity of this anaerobic test as a measure of peak power has been well established [98].

A modified version of the single-leg vertical jump as described by Barber et al. (1990) was performed [9]. With hands behind the back, to limit the effects of arm movement on the jump and to ensure the reflective marker on the subject's greater trochanter was visible, the subjects were instructed to jump as high as possible off the specified limb and land on the same limb. Prior to this, they were trained to bend the specified limb to a balanced semi-squat position and pause momentarily in this position in order to minimize the possibility of a counter-movement
jump. All subjects performed a total of three jump trials on each leg, alternating limbs. A rest period of up to two minutes between trials minimized the effect of fatigue.

Two-dimensional videotaping of the subjects' single-leg vertical jump performance was carried out and vertical distances achieved were determined using the Peak Performance Motion Measurement System (Peak Performance Technologies, Inc., Version 5.1.3). The vertical height attained was determined by the change in the vertical position of the subject's greater trochanter from quiet standing to the maximum height achieved. The highest jump from three trials was used. The vertical jump index (%) for the Controls was calculated by dividing the highest distance achieved on the non-dominant limb, by that of the dominant limb, and multiplying the result by 100. Whereas the vertical jump index (%) for the ACLD was determined by dividing the highest jump on the injured limb, by the highest jump on the non-injured limb, and multiplying this ratio by 100.

4.2.2.4 Confidence in Landing Scale

A profile of ACLD individuals demonstrated that a subluxation of the knee is most likely to occur at footstrike (or shortly after) during activities involving sudden changes in direction, quick stops and jumping movements [24]. Hence, the fear of subluxation on landing has been considered a possible cause in the reduction of the distance jumped in the OLHD in this population [106].

A situation specific, single item response continuum was developed for the purpose of this study to assess the level of confidence in landing the OLHD. Subjects were requested to rate their perceived level of confidence in landing the OLHD prior to attempting this functional task on a 0 to 100% response scale, with 0% indicating “not at all confident” and 100% denoting “completely confident” (Appendix 4). This scale was re-administered prior to performing the OLHD on the opposite limb.
4.2.2.5 Two Modified Versions of the OLHD

To analyze the contributions of take-off (mainly influenced by muscle function) versus landing (affected by fear of subluxation) to the horizontal distance achieved, subjects performed two modified versions of the OLHD. The first modified hop test, designed to assess the contribution of take-off, required subjects to hop from one limb and land on both. Whereas, the second modified hop test, developed to examine the contribution of landing, required subjects to hop from both and land on one limb.

With hands behind back to minimize the contribution of arm swing, subjects were instructed to hop as far forward as possible for both modified versions of the OLHD. All subjects performed a total of three trials for each of the two hop tests, on each limb. In the first modified hop test, subjects alternated the limb from which they hopped, whereas in the second modified hop test, subjects alternated the limb on which they landed. Up to two-minute rest periods were interspersed between each hop trial to minimize the effect of fatigue. The hop distance achieved was determined via a direct tape measurement from the established starting position to the point of heel contact on landing. The location of heel contact was easily identified since subjects had dipped the heel of their running shoes in coloured chalk prior to the test. For both hop tests, the longest hop of the three trials was used in the data analysis.

4.2.2.6 Perceived Disability (ACL-QOL Questionnaire)

The ACL-QOL questionnaire [127] is the first subjective knee scale to be validated for measuring quality of life in patients with chronic ACL deficiency. The questionnaire (Appendix 5) was administered to all subjects. The 32 separate items in 10-cm VAS response format were weighted equally to provide an overall score out of 100 [127].
4.2.3 Order of Testing

The order of testing was organized to minimize subject fatigue by interspersing questionnaires between strength and performance measures and adequate rest periods were provided in between consecutive trials. Written consent was sought and leg dominance was determined by asking the subject to identify the leg with which they would preferably kick a ball. Anthropometric measures including height, BWt, leg length, FFM and percentage of body fat via bioelectrical impedance, and waist girth were collected. In addition, knee measurements including knee swelling and ROM were gathered (not part of this thesis). Prior to commencing the strength and performance measures, the order of limb testing was randomly determined. Subjects warmed-up on a stationary bike for five minutes. A one RM test using the leg press was performed on each limb separately and the Modified Knee Scoring Scale of Lysholm questionnaire was completed thereafter. Subjects were then escorted to a different site (within the O&AI) where the filming of the performance of the single-leg vertical jump and OLHD took place. Subjects were prepped prior to the filming by affixing lightweight, reflective markers to specific bony prominences of the trunk and test limb. Thereafter, three trials of the single-leg vertical jump were performed and then three trials of the OLHD. Prior to the performance of the OLHD, subjects' scored their confidence in landing this task. The Tegner Activity Score questionnaire was completed while affixing reflective markers to the subject's opposite limb. The single-leg vertical jump, scoring of the confidence in landing scale and OLHD were then repeated on the opposite limb. Subsequently, subjects were escorted back to the original site of testing and performed three trials of the two modified versions of the OLHD on each limb. Subjects scored their confidence in landing prior to their performance of each of these tasks. Thereafter, the ACL-QOL questionnaire was administered followed by isokinetic muscular strength testing of the knee musculature on each limb separately. All tests were administered by the same physical therapist according to a standardized protocol throughout the study.
4.4 STATISTICAL ANALYSIS

SigmaStat for Windows (Version 2.03 Copyright © 1992-1997 SPSS Inc.) was used for all statistical computations and SigmaPlot for Windows (Version 4.01 Copyright © 1986-1997 SPSS Inc.) was employed for the graphical representation of the data.

A formal sample size calculation was performed for this study to ensure that the expected difference in the absolute hop distance between ACLD and healthy non-injured Controls would be detected with a power of 0.80 and probability of 0.05. The literature was examined for studies with similar populations, and descriptive statistics pertaining to the hop distance of the OLHD were collected [116, 118]. The sample size required to detect a difference of 20 to 32 cm between ACLD and Control group with a power of 0.80, at a probability of 0.05 was calculated to be eight to ten subjects within each group. To safeguard against the possibility of incomplete tests the sample included ten per group for a total of 20 subjects.

Comparisons between groups with respect to descriptive measures (i.e., anthropometric measures) were tested using independent t-tests. The remaining statistical analyses are presented with reference to the research questions posed within this thesis.

Differentiating between ACLD and healthy, non-injured samples using OLHD scores

*Do OLHD scores differentiate between ACLD and a healthy non-injured sample? Can the separation in OLHD scores between ACLD and Controls be increased upon controlling for differences in inherent athletic ability and leg dominance?*

The difference in hop distance and hop index scores between ACLD and Controls was determined using independent t-tests. Subsequently, ACLD and Controls were retrospectively matched in order to control for differences in inherent athletic ability and leg dominance.
(Appendix 6) and the difference between scores corrected for these two sources of error were tested using paired t-tests. The 95% confidence intervals for the differences in raw scores, scores corrected for inherent athletic ability and scores corrected for leg dominance were compared to determine the degree of separation between the ACLD and Controls.

**Diagnostic ability of the hop index**

*Do the established clinical benchmarks for normal versus abnormal limb symmetry discriminate between an ACLD and a healthy non-injured sample? Can the diagnostic ability of the hop index be improved upon by controlling for differences in inherent athletic ability and leg dominance?*

Sensitivity and specificity of the hop index, in its raw form, corrected for differences in inherent athletic ability and corrected for leg dominance, were evaluated by classifying the hop index as normal or abnormal according to the widely used hop index reference norms and a comparison was made.

Limitations pertaining to the diagnostic ability of the hop index were further explored through: 1) an analysis of the distribution of the hop distance scores using scatterplots; 2) an investigation of the relationships between the hop index and hop distance scores within each group using Pearson’s Product Moment Correlations and 3) an exploration of the association between hop distance scores within each group using Pearson’s Product Moment Correlations. Based on the relationships found, the hop distance scores underwent a data transformation (log10) to minimize the effect of the arithmetic variation of the proportional differences. Subsequently, the hop indexes were re-calculated from the transformed hop distance scores and the distributions of the transformed hop index scores within the normal versus abnormal hop index categories were analyzed.
Determinants of OLHD performance

How does muscle function and confidence in landing differ between ACLD and matched Controls? How do differences between ACLD and matched Controls in muscular function and confidence in landing compare with differences in their OLHD performance? What is the relationship between muscle function, confidence in landing and OLHD performance in the ACLD and matched Controls? What is the relationship between the decline in muscular strength and confidence to the loss in the ability to hop secondary to an ACL injury? What are the contributions of take-off (influenced by muscular function) versus landing (affected by fear of subluxation) on OLHD performance?

An analysis of the mean differences in muscular function and confidence in landing was carried out on the matched pairs (Appendix 6-Table 22) using paired t-tests. A comparison of the variation between ACLD and matched Controls in muscular function, confidence in landing and OLHD were analyzed by way of confidence intervals. The relationships between muscular function, confidence in landing and OLHD performance and between the decline in muscular function and confidence in landing to the loss in ability to hop secondary to ACL injury were explored by way of Pearson Product Moment Correlations. Finally, two versions of the OLHD were compared to assess the contributions of take-off versus landing to distance hopped.

Comparisons between ACLD and Controls (matched pairs) of distance hopped and level of confidence in landing for the two versions of the OLHD were carried out using paired t-tests.

Relationship of OLHD performance to perceived disability

To what extent do the ACLD differ in their perceptions of disability relative to matched Controls? How do differences between ACLD and matched Controls in perceived disability compare with differences in their OLHD performance? What is the relationship between OLHD performance
and perceived disability? What is the relationship between an increase in perception of disability to the loss in ability to hop for distance secondary to an ACL injury?

An analysis of the mean differences in perceived disability (ACL-QOL scores) was carried out on the matched pairs (Appendix 6-Table 22) using paired t-tests. Differences in ACLD and Controls perceptions of disability and OLHD performance were compared by way of confidence intervals. The relationships between perceived disability and OLHD performance and between the increase in perceived disability and the loss in ability to hop secondary to an ACL injury were explored by way of Pearson Product Moment Correlations.

All differences were deemed significant at the p ≤ 0.05 level. Correlations were considered strong if r ≥ 0.70, moderate if 0.40 ≥ r ≤ 0.69 and poor if r ≤ 0.39.
5.1 SUBJECT DESCRIPTION

The following section provides a description of subjects tested. This information includes: age, sex, time post ACL injury, concomitant knee pathologies, Modified Lysholm Knee score, Tegner Activity score, overall IKDC knee profile score, ligamentous laxity grade and anthropometric measures.

All subjects (ACLD, n=10 and Controls, n=10) were males. The mean (+SEM) ages of each group were equal: ACLD 28.4 (±2.74) years and Controls 28.4 (±1.11) years. The ACLD were tested 5.3 to 60 months post injury (26.1± 5.02 months). The affected limb was the dominant limb in 40% of the cases (n=4). None of the ACLD subjects had undergone ligamentous reconstructive surgery prior to testing however, 40% reported (n=4) having previously undergone an arthroscopic debridement of the involved knee.

All ACLD subjects underwent an arthroscopic repair of their torn ACL within nine days post testing. Confirmation that all ACLD subjects had sustained a complete disruption of their ACL was provided upon arthroscopic examination at the time of repair. Other knee pathologies found arthroscopically included: meniscal tears (medial meniscus (n=6), lateral meniscus (n=1) and tears in both menisci (n=2)); synovitis (n=2); early chondrosis (retropatellar surface (n=1), trochlear groove (n=1) and medial femoral compartment (n=1)); grade 1 degenerative changes (medial compartment (n=1), medial facet of the patella (n=1) and intercondylar spine (n=1)); grade 1 or 2 softening of the lateral femoral condyle (n=2); grade 2 or 3 medial facet patellar chondromalacia (n=1); and previous menisectomy (n=2).
5.1.1 Knee Scoring Scales

Scores on the Modified Knee Scoring Scale of Lysholm (median; 25th; 75th percentiles) for the Control group (100; 100; 100) were significantly greater than those of the ACLD (79.5; 72; 90), p=<0.001. This implies that the ACLD reported greater knee symptomatology and limitations with specific functional tasks relative to Controls.

The accompanying Tegner Activity Score demonstrated that a total of 70% of the Controls (n=7) took part in recreational or competitive sports (activity levels five to ten) and the remaining pursued activities of daily living exclusively (activity levels zero to four). Whereas, at the time of testing, 50% of the ACLD subjects (n=5) took part in recreational or competitive sporting activities and the remaining pursued activities of daily living only.

The difference in Lysholm Scores between the ACLD individuals who took part in recreational or competitive sporting activities (84; 78.25; 95) versus those who took part in activities of daily living only (72; 68.25; 82.5) was not significant (p (exact)=0.15) which is likely attributed to the small sample investigated. Nevertheless, those ACLD individuals who reported having 'good' (Lysholm score between 84 to 94) lower limb function were more likely to be involved in recreational and competitive sports compared to those who reported 'fair' (Lysholm score between 65 to 83) knee function (Appendix 7).

With respect to the overall IKDC grade, 60% of the ACLD subjects (n=6) were evaluated as having an Abnormal (C) knee profile and the remaining 40% (n=4) demonstrated a Severely Abnormal (D) knee profile. The ligamentous stability component of the IKDC confirmed that none of the ACLD subjects demonstrated multi-ligamentous laxity. With respect to the ACL manual stress tests, 80% of the ACLD (n=8) were graded as having Abnormal laxity (C) and 20% (n=2) as having Severely Abnormal (D) laxity.
5.1.2 Anthropometric Measures

ACLD and Controls did not differ significantly (p>0.05) in height, waist girth, leg length and percentage of body fat. However, the ACLD group was 13% heavier (p= 0.009), had a 9% higher BMI (p=0.013) and a 14% higher FFM (p=0.008) compared to the Control group (Table 8). In short, the ACLD group was heavier and leaner compared to their age and gender matched Controls.

ANTHROPOMETRIC CHARACTERISTICS

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>CONTROLS</th>
<th>ACLD</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>1.8 (+/-0.02)</td>
<td>1.8 (+/-0.03)</td>
<td>0.43</td>
</tr>
<tr>
<td>BWt (kg)</td>
<td>73.4 (+/-2.2)</td>
<td>82.7 (+/-2.3)</td>
<td>0.009*</td>
</tr>
<tr>
<td>BMI (kgm⁻²)</td>
<td>24.0 (+/-0.7)</td>
<td>26.2 (+/-0.5)</td>
<td>0.013*</td>
</tr>
<tr>
<td>Waist Girth (cm)</td>
<td>81.6 (+/-2.3)</td>
<td>85.2 (+/-1.8)</td>
<td>0.242</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>20.8 (+/-1.0)</td>
<td>19.3 (+/-1.9)</td>
<td>0.503</td>
</tr>
<tr>
<td>FFM (kg)</td>
<td>58.2 (+/-1.9)</td>
<td>66.6 (+/-2.0)</td>
<td>0.008*</td>
</tr>
<tr>
<td>Average Leg Length (cm)</td>
<td>92.9 (+/-1.1)</td>
<td>93.4 (+/-1.7)</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Table 8 Summary of mean (+ SEM) anthropometric characteristics by group. Mean values were compared using independent t-tests (* indicates p< 0.05).

BMI was calculated from height and BWt measures. Percentage of body fat and FFM were estimated from BIS. Average leg length was calculated from taking the average of the dominant and non-dominant leg lengths within each individual.
5.2 OLHD SCORES

The difference between the hop distance on the non-injured limb of the ACLD and the average limb performance of the Controls was assessed to determine comparability of the groups with respect to OLHD performance. The mean (±SEM) hop distance on the non-injured limb of the ACLD group was 1.72 (±0.06)m and the mean hop distance of the average limb performance in the Control group was 1.76 (±0.05)m demonstrating a mean difference of only 0.03m which was not significant when assessed using an independent t-test (p=0.67). Thus, OLHD performance on the non-injured limb in the ACLD group is comparable to that of the Controls despite differences in BMI and lean body mass.

The ensuing sections explore: 1) the variation in OLHD scores between ACLD and healthy, non-injured Controls and, if controlling for differences in inherent athletic ability and the impact of leg dominance, better separate the two groups (Section 5.2.1) and; 2) the diagnostic ability of the hop index and, if correcting for differences in inherent athletic ability and the impact of leg dominance, improves the sensitivity of the hop index in detecting abnormal limb symmetry in the ACLD (Section 5.2.2).

5.2.1 Differences in OLHD Scores between ACLD and Controls

5.2.1.1 Raw Scores

Upon examination of the raw scores, the Controls demonstrated the expected less than 15% limb asymmetry [9, 13] with the exception of one subject, who demonstrated a 19% limb difference (119% hop index), hopping further with the non-dominant limb (left) compared to the dominant limb (right). During the initial interview, this subject reported that he had sustained multiple sprains of his right ankle in the past, but reassured the writer that there were no residual problems. Given that he did not hop as far on the right limb and the amount of limb
asymmetry is in excess of what is deemed to be within normal limits in a healthy, non-injured population [9, 13], this subject was excluded from the remaining analyses.

Statistically significant differences in mean hop distance score between the ACLD limb and average of limbs within the Controls (12%) in addition to the mean hop index score between the ACLD and Control group (10%) were found (Table 9).

<table>
<thead>
<tr>
<th>Subject ID No.</th>
<th>Age (y)</th>
<th>Gender</th>
<th>ACLD Affect (dom/nondom)</th>
<th>Controls Average of dom/nondom limbs</th>
<th>ACLD Hop Index (dom/nondom limbs)</th>
<th>Controls Hop Index (non-dom/dom)</th>
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</thead>
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<tr>
<td>1</td>
<td>1.59</td>
<td>1.92</td>
<td>84</td>
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<tr>
<td>2</td>
<td>1.44</td>
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<td>88</td>
<td>100</td>
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</tr>
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<td>3</td>
<td>1.52</td>
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<td>86</td>
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<td>103</td>
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<td>8</td>
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<tr>
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<tr>
<td>10</td>
<td>1.51</td>
<td>2.06</td>
<td>96</td>
<td>107</td>
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<td></td>
</tr>
</tbody>
</table>

Table 9 Raw scores and means (±SEM) of hop distance and hop index scores by group. Mean values were compared using independent t-tests (* indicates p < 0.05). The Control subject that was eliminated (identified by the strikethrough) was not included in the above analysis.

The hop distance on the ACLD [affected (aff) limb] was compared to Controls [average of dominant (dom) and non-dominant (nondom) limbs]. The hop index was calculated by dividing the hop distance on the affected limb by the unaffected limb (aff/unaff) for the ACLD and the non-dominant divided by the dominant (non-dom/dom) for the Controls.

5.2.1.2 Scores Corrected for Differences in Inherent Athletic Ability

Differences in hop distance scores due to inherent athletic ability between patients were controlled through retrospective matching in an attempt to isolate differences due to ACL injury.

Upon retrospectively matching ACLD and Controls, according to distance hopped on the unaffected limb of the ACLD to the average limb performance of the matched Control
differences in OLHD scores were explored. The mean differences in hop distance and hop index among the identified pairs were statistically significant (Table 10).

<table>
<thead>
<tr>
<th>Matched Pairs</th>
<th>Hop Distance (cm)</th>
<th>Hop Index (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject IDNO:</td>
<td>Difference between ACE and Controls (average of dom and non-dom limb)</td>
<td>Difference between ACE and Controls (aff/unaff and matched Controls)</td>
</tr>
<tr>
<td>1 → 2</td>
<td>-0.34</td>
<td>-0.16</td>
</tr>
<tr>
<td>2 → 9</td>
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<td>-0.12</td>
</tr>
<tr>
<td>3 → 3</td>
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<td>-0.23</td>
</tr>
<tr>
<td>4 → 5</td>
<td>-0.13</td>
<td>-0.04</td>
</tr>
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<td>5 → 10</td>
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<td>-0.23</td>
</tr>
<tr>
<td>6 → 8</td>
<td>0.03</td>
<td>0.12</td>
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<tr>
<td>7 → 1</td>
<td>-0.26</td>
<td>-0.06</td>
</tr>
<tr>
<td>8 → 6</td>
<td>-0.93</td>
<td>-0.19</td>
</tr>
<tr>
<td>9 → 4</td>
<td>-0.22</td>
<td>-0.13</td>
</tr>
<tr>
<td>10 → 7</td>
<td>-0.14</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

Table 10: Paired and mean (±SEM) differences in hop distance and hop index corrected for differences in inherent athletic ability. Mean differences were compared using paired t-tests (* indicates p<0.05). The eliminated Control subject and its matched ACLD pair (identified by the strikethrough) were not included in the analyses.

ACLD and Controls were matched according to the hop distance on the unaffected limb of the ACLD and the average (dom and non-dom) limb performance of the matched Control (Appendix 6-Table 21).

5.2.1.3 Scores Corrected for Differences in Leg Dominance

Although leg dominance did not have a significant effect on hop distance in the healthy, non-injured sample (absolute difference between limbs within the Control group =0.02m; p=0.441), this dynamic may not be the same in an injured sample.

In the ACLD population, the hop distance is reported in terms of their injured and non-injured limb whereas in a healthy population, the hop distance is usually reported in terms of their non-
dominant and dominant limb. Similarly, in the ACLD population the hop index is expressed as the hop distance achieved on the injured limb relative to that of the non-injured limb. Whereas in a healthy population, the hop index is typically expressed as the hop distance achieved on the non-dominant relative to the dominant limb. Consequently, the impact of leg dominance is not corrected for in either of the OLHD scores in the ACLD population. This may result in masking or exaggerating functional limitations in the performance of the OLHD when comparing the ACLD knee to an uninjured knee (for both within and between patient comparisons).

Differences in OLHD scores due to the impact of leg dominance in the ACLD sample were controlled for through retrospective matching in an attempt to isolate differences due to ACL injury. Upon retrospectively matching ACLD to Controls, according to the hop distance on the ACLD unaffected limb and the hop distance of the matched Control of the same limb dominance (Appendix 6-Table 22), the mean differences in OLHD scores were explored. Results demonstrated that the mean differences in hop distance and hop index among the identified pairs were statistically significant (Table 11).
Table 11 Paired and mean differences (+SEM) in hop distance and hop index corrected for variation due to leg dominance. Mean differences were compared using paired t-tests (* indicates p<0.05). The eliminated Control subject and its matched ACLD pair (identified by the strikethrough) were not included in the above analysis.

ACLD and Controls were matched according to the hop distance on the unaffected limb of the ACLD and the hop distance of the matched Control of same limb dominance (Appendix 6-Table 22).

In summary, the ACLD limb demonstrated an impaired performance of the OLHD relative to healthy Controls for both hop distance and hop index. This finding was evident upon investigation of the raw scores, scores corrected for differences in inherent athletic ability and scores corrected for leg dominance. A comparison of the lower limits of the 95% confidence interval for the hop distance and hop index scores was carried out to determine if the separation between the two groups increased upon controlling for differences in athletic ability and leg dominance.

Examination of the lower limits of the 95% confidence interval for the differences in ACLD and Controls in hop distance scores using: a) raw scores; b) scores corrected for differences in inherent athletic ability and c) scores corrected for leg dominance demonstrated a substantial
increase in the separation between groups upon correcting for differences in inherent athletic ability. Whereas, controlling for leg dominance (in addition to inherent athletic ability) had little impact on the separation between the ACLD and Controls (Figure 5).

**Figure 5** Summary of the 95% confidence intervals for the differences in ACLD and Controls mean hop distances using raw scores, scores corrected for differences in inherent athletic ability and scores corrected for differences attributed to leg dominance.

The lower limits for the 95% confidence intervals for the differences between ACLD and matched Controls in hop index scores using: a) raw scores; b) scores corrected for differences in inherent athletic ability and c) scores corrected for differences in leg dominance (in addition to inherent athletic ability) demonstrated similar separation between ACLD and Controls. Thus, correcting for inherent athletic ability and leg dominance had minimal to no impact on increasing the separation between ACLD and Controls hop index scores (Figure 6).
Figure 6 Summary of the 95% confidence intervals for the differences in ACLD and Controls mean hop indexes using raw scores, scores corrected for differences in inherent athletic ability and scores corrected for differences attributed to leg dominance.

In summary, the differences between ACLD and Controls in hop distance and hop index scores were significant. Regarding the hop distance, the distinction between the ACLD and Controls increased substantially upon controlling for differences in inherent athletic ability; however, controlling for leg dominance had no further impact. With respect to the hop index, correcting for differences in inherent athletic ability and leg dominance had minimal to no impact on increasing the separation between ACLD and Controls.

5.2.2 Diagnostic Ability of the Hop Index

The preceding results imply that the OLHD reliably differentiates between samples, but not necessarily individuals. Upon exploring the percentage of subjects in the abnormal hop index categories, as defined by Barber et al. (1990) and Daniel et al. (1982 and 1988) [9, 105, 115], the percent probability of detecting an abnormal hop index in the ACLD is poor (low sensitivity).
However, the percent probability of detecting a normal hop index in normal knees is good (high specificity) (Table 12 and Figure 7).

**Sensitivity and Specificity of the Hop Index in the Assessment of ACL Injuries**

<table>
<thead>
<tr>
<th></th>
<th>ACLD</th>
<th>CONTROLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abnormal</td>
<td>20%</td>
<td>0%</td>
</tr>
<tr>
<td>(≤85%&lt;sup&gt;1&lt;/sup&gt;)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>80%</td>
<td>100%</td>
</tr>
<tr>
<td>(≥85%&lt;sup&gt;1&lt;/sup&gt;)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>ACLD</th>
<th>CONTROLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abnormal</td>
<td>50%</td>
<td>0%</td>
</tr>
<tr>
<td>(≤90%&lt;sup&gt;2&lt;/sup&gt;)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>50%</td>
<td>100%</td>
</tr>
<tr>
<td>(≥90%&lt;sup&gt;2&lt;/sup&gt;)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 12 Summary of the percentage (%) of tests that yielded abnormal results in the ACLD (low sensitivity), % of tests that demonstrated normal hop index in the Controls (high specificity), % of tests that demonstrated normal hop index in an ACLD (high false-negative) and the % of tests that demonstrated an abnormal hop index in Controls (low false-positive).

<sup>1</sup>Barber et al. (1990) and <sup>2</sup>Daniel et al. (1982 and 1988) hop index reference norms [9, 105, 115].
Figure 7 Distribution of the ACLD and Controls hop index scores. Only 20% of the ACLD subjects (n=2) demonstrated an abnormal hop index (<85%) according to reference norms as defined by Barber et al (1990) [9] whereas 50% of the ACLD subjects (n=5) had an abnormal hop index (<90%) according to reference norms defined by Daniel et al. (1982 and 1988) [105, 115]. All of the Controls (n=9) demonstrated normal limb symmetry (>90%).

The method by which the hop index was calculated may have an impact on the distribution of the hop index scores within the Control group. Therefore, the hop indexes from the different definitions found within the literature were calculated (non-dominant/dominant, left/right and lesser/greater) and their distributions examined. Upon comparison, all of the Controls demonstrated a hop index of greater than 90% regardless of the method employed. Therefore, the method by which the hop index is calculated had no impact on the number of Controls that were classified as having a normal versus abnormal hop index.
Therefore, although differences between ACLD and Controls in mean hop index scores were significant (see Section 5.2.1), the individual variation in hop index scores was not great enough to consistently discriminate each ACLD subject from Controls using the established clinical benchmarks for normal versus abnormal limb symmetry.

Differences in inherent athletic ability and the effect of leg dominance were not factors in the sensitivity of the hop index in the detection of lower limb functional nevertheless, an approach for dealing with these two factors has been suggested in Appendix 8.

An analysis of the hop distances achieved on the injured and non-injured limbs of the ACLD and the non-dominant and dominant limbs of the healthy, non-injured Controls revealed less variation of the hop distance scores on the injured limb within the ACLD group (see Figure 8).

**Scatterplots of the distance hopped by the ACLD and Controls**

![Image of Scatterplots](image)

**Figure 8** Scatterplots of the absolute distances hopped (m) on the injured and non-injured limbs of the ACLD and the non-dominant and dominant limbs of the healthy, non-injured Controls.
This lead us to speculate that regardless of the hop distance achieved on the non-injured limb, the hop distance achieved on the injured limb are somewhat similar within the ACLD sample. Hence, the hop index is more sensitive in those ACLD individuals that hop farther on their non-injured limb. To explore this farther, correlations between hop distance and hop index were carried out in the ACLD and Controls groups separately.

The Control group did not demonstrate an association between the hop distance (average of both limbs) and the hop index ($r=0.32; p=0.40$), as all Controls demonstrated a relatively symmetrical hop index irrespective of actual distance hopped (Figure 9).

**Relationship between Hop Index and Average Hop Distance within the Controls**

![Graph](image)

**Figure 9** This Pearson Product Moment Correlation illustrates the lack of association between the Hop Index (non-dominant / dominant $\times 100$) and the Hop Distance (average of limbs) in the Control group ($r=0.32; p=0.40$).
Conversely, the ACLD group demonstrated a moderate-strong correlation between the hop index and hop distance on the non-injured limb ($r = -0.66, p=0.04$) (Figure 10). This finding was verified by way of a regression analysis ($F$ value=6.08; $p=0.039$) which confirmed that a significant relationship exists between hop index and distance hopped on the non-injured limb of the ACLD.

**Relationship between Hop Index and Hop Distance on the ACLD Non-Injured Limb**

![Pearson Product Moment Correlation Plot](image)

**Figure 10** This Pearson Product Moment Correlation plot illustrates the moderate-strong association between the Hop Index (injured / non-injured $\times 100$) and the Hop Distance (non-injured limb) in the ACLD group.

This finding suggests that the hop distance achieved on the non-injured leg is associated with the hop index within the ACLD group. More specifically, the farther the distance hopped on the non-injured limb, the poorer the hop index. Conversely, the lesser the distance hopped on the non-injured limb, the better the hop index. Therefore, controlling for differences in distance hopped on the uninjured limb (inherent athletic ability) may be important in computing the hop index in the ACLD so that the hop distance is less of a critical factor.
Upon evaluation of the injured limb, the distance achieved is not a consideration with respect to the hop index as there was no association between the hop index and hop distance on the injured limb ($r=0.10; p=0.79$) (Figure 11).

**Relationship between Hop Index and Hop Distance on the ACLD Limb**

![Graph showing the relationship between Hop Index and Hop Distance on the ACLD Limb](image)

*Figure 11 This Pearson Product Moment Correlation illustrates the lack of association between the Hop Index (injured / non-injured x 100) and the Hop Distance (injured limb) in the ACLD group ($r=0.10; p=0.79$).*
Based on the preceding findings, the variability among the hop distance scores within the ACLD and Control group warranted further examination. Comparison of the relationship between limbs in hop distance performance within the ACLD revealed a moderate to high correlation ($r=0.68; \ p=0.04$) whereas, between limb performance within the Control group demonstrated a very high correlation ($r=0.91; \ p<0.001$) (Figure 12).

Figure 12 These Pearson Product Moment Correlations illustrate a moderate-strong association between limbs (Non-injured Vs Injured) within the ACLD group ($r=0.68; \ p=0.04$) and a very strong association in the Hop Distance between limbs (Dominant Vs Non-dominant) within the Control group ($r=0.91; \ p<0.001$).

The clustered appearance of the hop distance scores on the injured limb, relative to the non-injured limbs of the ACLD and Controls, illustrates the narrower range of hop distance scores on the ACLD limb. The decreased variability among the hop distance scores of the ACLD limb
results in a poorer hop index score in those ACLD individuals that hop farther on their non-injured leg compared to those who hop less. Therefore, the hop index is more sensitive for those ACLD individuals who hop farther on their non-injured limb.

In order to minimize the arithmetic variation between limb performance of the ACLD and Controls, the hop distance scores were transformed using a $\log_{10}$ transformation; however, logarithms to any base would have had the same effect [145-147]. Subsequently, the hop indexes for both samples were recalculated (Table 13), the separation between the ACLD and Controls' original and transformed hop index scores were re-assessed (Figure 13) and the distributions of the transformed hop indexes within the normal and abnormal categories were re-analyzed (Figure 14).
### Original and Transformed Hop Distance Scores and Corresponding Hop Indexes

**CONTROLS: Original**

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<thead>
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</tr>
</thead>
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- **Logged Data**

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**ACL: Original**

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- **Logged Data**

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**Table 13** Summary of the original and transformed hop distance scores, the corresponding hop indexes, means and standard deviations (s.d.) for both Controls (n=9) and ACLD (n=10) subjects. Original hop distance scores of the Controls and ACLD were transformed using the log<sub>10</sub> transform. The hop index scores within the Control group were calculated by dividing the non-dominant (Non-Dom) by the dominant (Dom) limb hop distance scores whereas in the ACLD group, the hop index scores were calculated by dividing the injured limb by the non-injured limb hop distance scores.
Scatterplots of the Original and Transformed Hop Index Scores

Figure 13 Scatterplots of the ACLD and Control hop indexes based on the original and transformed (log_{10}) hop distance scores. There is greater separation between the ACLD and Control hop index scores upon transforming the underlying hop distance scores.
Distribution of the Original and Transformed Hop Index Scores

Controls

ACLD

Figure 14 Summary of the distribution of the hop index scores calculated from the original and transformed \(\log_{10}\) hop distance scores for Control and ACLD subjects. All Controls demonstrated a normal hop index (>90%) upon examination of the hop indexes calculated from the original and transformed \(\log_{10}\) hop distance scores. Whereas, the percentage of ACLD patients that demonstrated an abnormal hop index increased from 20 to 60% using the hop index reference norm (> 85%) defined by Barber et al. (1990) [9] and from 50 to 70% using the reference norm (>90%) defined by Daniel et al. (1982 and 1988) [105, 115].
In summary, the differences attributed to inherent athletic ability (hop distance on non-involved limb) is a critical factor in terms of the sensitivity of the hop index scores in the ACLD subjects only. Transformation of the hop distance scores, using a log_{10} transformation, minimized the arithmetic variation between the proportional differences. As a result, the separation between the ACLD and Controls hop index scores increased when calculated from the transformed hop distance scores and the sensitivity of the hop index as a diagnostic tool in the detection of functional limitations as a result of ACL injury improved.
5.3 VARIATIONS BETWEEN ACLD AND CONTROLS IN IMPAIRMENTS AND PERCEIVED DISABILITY RELATIVE TO OLHD PERFORMANCE

5.3.1 Measures of Muscle Function

5.3.1.1 Isokinetic Concentric Quadriceps Strength

Isokinetic concentric quadriceps strength (PT BW⁻¹) of the unaffected limb of the ACLD and their matched Controls did not differ significantly at any of the given limb velocities. The difference between the ACLD limb and their matched Controls was significant at 120° s⁻¹ (p=0.03) however, not at speeds of 60° s⁻¹ (p=0.06) or 180° s⁻¹ (p=0.10) (Table 14 and Figure 15).

Figure 15 Summary of the mean differences (±SEM) in isokinetic concentric quadriceps strength at 60, 120 and 180° s⁻¹ between: 1) ACLD affected limb and matched Controls and; 2) ACLD unaffected limb and matched Controls. Significant mean differences at p<0.05 are identified with an asterisk (*).

The transformed hop index scores discriminate between ACLD and matched Controls better than either the original hop index scores or the isokinetic concentric quadriceps strength at 120° s⁻¹. This is indicated by the 95% confidence intervals as demonstrated in Table 14 and Figure 19.
5.3.1.2 One RM Leg Press Ability

There was no significant difference in one RM leg press ability (kg / BWt) between the
unaffected limb of the ACLD and their matched Controls. In addition, the ACLD limb
demonstrated a small, non-significant reduction in leg press ability relative to their matched
Controls (Table 14).

A factor that may have affected the accuracy of these test results was the limited ability to
increase the distance between the test seat and the foot-plate. Although every effort was made
to ensure that each subject demonstrated approximately 90 degrees of knee flexion prior to
testing, patients with differing leg lengths who sat with the seat adjusted furthest away from the
foot-plate would have differing degrees of knee flexion. This may have inhibited the longer
legged subjects in initiating movement of the foot-plate with progressively heavier loads due to
an increased amount of knee flexion and patellofemoral joint stress [149].

To test whether or not leg length influenced the results, the relationship between leg length and
one RM leg press ability was explored in our healthy, non-injured sample. Results revealed that
upon correcting for BWt, the average one RM leg press was poorer in those with longer legs
(r= -0.68; p=0.04). In fact, leg length explained approximately 46% of the variability in one RM
leg press results.

To rule out the possibility that the association between leg length and one RM leg press ability
may have been attributed to differences in BWt or FFM, the relationship between leg length and
these two measures of body composition were explored. Results revealed poor, non-significant
correlations between average leg length and BWt (r=0.06, p=0.873) and average leg length and
FFM (r=0.04, p=0.923).
Therefore, the reduced one RM leg press ability in the longer legged subjects was likely due to the greater degree of knee flexion in the initial test position as a result of the limited ability to adjust the seat farther away from the foot-plate. Due to this source of error, further analysis and discussion pertaining to muscular function will exclude results pertaining to the one RM leg press.

5.3.1.3 Single-Leg Vertical Jump

The unaffected limb of the ACLD and their matched Control did not differ significantly with respect to the maximum vertical height achieved upon performing the single-leg vertical jump (p=0.60) however, the ACLD jumped significantly less with their injured limb compared to their matched Controls (Table 14 and Figure 16).

![Figure 16](image)

**Figure 16** Summary of the mean differences in the maximum height achieved in the single-leg vertical jump between: 1) ACLD affected limb and matched Controls and; 2) ACLD unaffected limb and matched Controls. Significant mean differences at p<0.05 are identified with an asterisk (*).

Single-leg vertical jump index scores, computed as per OLHD hop index scores, demonstrated a mean (± SEM) score of 89.4 (±6.02)% for the ACLD and 103.5 (±4.73)% for the Controls. The mean differences in vertical jump index scores between the ACLD and their matched Controls was 14.1% (p-value=0.047). The vertical jump score was less effective at differentiating between ACLD and their matched Controls compared to the original and
transformed hop index scores as indicated by the 95% confidence intervals as demonstrated in Table 14 and Figure 19.

5.3.2 Confidence in Landing
A large difference in self-report ratings for confidence in landing between ACLD affected limb and their matched Controls was observed (p=0.004). Whereas, the difference between ACLD unaffected limb and their matched Controls with respect to confidence in landing was not significant (Table 14 and Figure 17).

Figure 17 Summary of the mean differences in confidence in landing the OLHD between: 1) ACLD affected limb and matched Controls; 2) ACLD unaffected limb and matched Controls. Significant mean differences at p<0.05 are identified with an asterisk (*).

A comparison of the lower limits of the 95% confidence interval between the confidence in landing scores and the hop index scores demonstrated that the variation between the subject's confidence relative to the variation in their hop index scores was greater (Table 14 and Figure 19).
5.3.1 **Perceived Disability (ACL-QOL Questionnaire)**

The mean difference in the ACL-QOL scores between the ACLD and their matched Controls was significant at the p<0.001 level (Table 14 and Figure 18).

![Bar chart showing mean difference in QOL scores between ACLD and matched Controls](chart.png)

**Figure 18** The mean difference between ACLD and matched Controls in ACL-QOL scores was found significant (*) at the p<0.001 level.

The variation between the ACLD and their matched Controls ACL-QOL scores relative to their hop index scores was much greater upon comparing the lower limits of the 95% confidence interval between the ACL-QOL score and the original and transformed hop index scores (Table 14 and Figure 19).
Figure 19 Summary of the 95% confidence intervals for the difference of means between ACLD and matched Controls in isokinetic concentric quadriceps strength, confidence in landing, ACL-QOL scores, single-leg vertical jump index scores and hop index scores (original and transformed) found significant at the p<0.05 level.

* the greatest difference in isokinetic concentric quadriceps strength at 120° s⁻¹ between ACLD and matched Controls.

In summary, the ACLD demonstrated an impaired hop performance, weaker concentric quadriceps strength at 120° s⁻¹, a reduction in their ability to jump vertically, reported less confidence in landing the OLHD and perceived themselves to be more disabled relative to Controls. However, the separation between the ACLD and Controls in quadriceps strength and ability to jump vertically was negligible relative to the separation found between groups in terms of their hop performance (transformed scores), reported confidence in landing and perceived disability.
Table 14 Summary of the means (±SEM), mean differences (±SEM) and 95% confidence intervals between ACLD and matched Controls in: isokinetic concentric quadriceps strength (at 60, 120 and 180°s⁻¹); one RM leg press ability; single-leg vertical jump; confidence in landing, ACL-QOL scores, hop index (original and transformed) scores. Mean differences were compared using paired t-tests except for the mean difference in confidence in landing ratings between ACLD unaffected and their matched Controls (~) which failed the test of normality hence a Wilcoxon Signed Rank Test was used (* indicates p<0.05). The variation between ACLD and Controls with respect to isokinetic strength, single-leg vertical jump, confidence in landing, perceived disability and OLHD performance was assessed using a 95% Confidence Interval for each measure.

ACLD and Control data were paired according to the hop distance on the unaffected limb of the ACLD and the hop distance of the Control of same limb dominance. Strength scores (isokinetic concentric quadriceps strength and one RM leg press ability) were divided by subjects' BWt in order to utilize a relative versus absolute measure of strength to control for the effects of BWt.
RELATIONSHIPS BETWEEN IMPAIRMENTS, PERCEIVED DISABILITY AND OLHD PERFORMANCE SECONDARY TO ACL INJURY

The differences between ACLD and matched Controls in OLHD performance were correlated to the differences in ACLD and matched Controls in 1) muscle function; 2) confidence in landing and 3) perceived disability to establish the relationships between OLHD performance and these variables consequent to ACL injury. Both hop distance and hop index scores (original and transformed) were used to define OLHD performance in the above correlational analyses (Table 15).

5.4.1 Differences between ACLD and matched Controls hop distance scores correlated to the differences between ACLD and matched Controls muscular function, confidence in landing and perceived disability

Strong and significant correlations were found between the differences in ACLD and matched Controls hop distance scores and isokinetic quadriceps strength at 120° s⁻¹ (r=0.69; p=0.040) and 180° s⁻¹ (r=0.77; p=0.014) (Figure 20).

Relationship between the differences in ACLD and matched Controls Hop Distance Scores and Isokinetic Concentric Quadriceps Strength at 120 and 180°s⁻¹

Figure 20 demonstrates the significantly strong correlations between the differences in ACLD and matched Controls hop distance scores and isokinetic quadriceps strength at 120° s⁻¹ (r= 0.69; p=0.040) and 180° s⁻¹ (r= 0.77; p=0.014).
A moderate, although non-significant, relationship was found between the differences in ACLD and matched Controls hop distance and ACL-QOL scores ($r=0.44$; $p=0.231$) (Figure 21).

**Relationship between the differences in ACLD and matched Controls**

**Hop Distance Scores and ACL-QOL**

![Graph](image)

**Figure 21** demonstrates the moderate, non-significant correlation between differences in ACLD and matched Controls hop distance scores and ACL-QOL ($r=0.44$; $p=0.231$).

Poor and non-significant relationships were demonstrated between the differences in ACLD and matched Controls hop distance scores and isokinetic quadriceps strength at 60° s⁻¹ ($r=0.36$; $p=0.334$), single-leg vertical jump ($r=0.04$; $p=0.91$) and confidence in landing ($r=-0.24$; $p=0.542$).

### 5.4.2 Differences between ACLD and matched Controls hop index scores correlated to the differences between ACLD and matched Controls muscular function, confidence in landing and perceived disability

Only moderate to poor, non-significant correlations were found between the differences in ACLD and matched Controls hop index scores and differences in the matched pairs' muscular function, confidence in landing and perceived disability. However, correlating the differences in ACLD and matched Controls transformed hop index scores to the differences between matched
pairs' muscular function, confidence in landing and perceived disability revealed similar relationships as demonstrated in section 5.4.1. For instance, strong and significant relationships were found between the differences in ACLD and matched Controls transformed hop index scores and the differences in matched pairs' isokinetic quadriceps strength at 120° s⁻¹ (r=0.74; p=0.021) and 180° s⁻¹ (r=0.70; p=0.038) (Figure 22).

Differences between ACLD and matched Controls Isokinetic Concentric Quadriceps Strength at 120 and 180°s⁻¹ versus Hop Index Scores (transformed)

Figure 22 demonstrates the significantly strong correlations in the differences between ACLD and matched Controls transformed hop index scores and isokinetic quadriceps strength at 120° s⁻¹ (r=0.74; p=0.021) and 180° s⁻¹ (r=0.70; p=0.036).

Moderate and non-significant relationships were found between the differences in ACLD and matched Controls transformed hop index scores and isokinetic quadriceps strength at 60° s⁻¹ (r=0.48; p=0.195) and ACL-QOL scores (r=0.48; p=0.193) (Figure 23).
Relationship between the differences in ACLD and matched Controls
Isokinetic Concentric Quadriceps Strength at 60° s⁻¹, ACL-QOL scores
and Hop Index Scores (transformed)

Figure 23 demonstrates the moderate non-significant correlations in the differences between
ACLD and matched Controls transformed hop index scores and isokinetic quadriceps strength
at 60° s⁻¹ (r= 0.48; p= 0.195) and ACL-QOL scores (r=0.48; p=0.193).

Finally, poor and non-significant relationships were found between differences in matched pairs’
hop index scores (calculated from transformed hop distance scores) and differences in matched
pairs’ single-leg vertical jump (r=-0.108; p=0.783) and confidence in landing (r = -0.20; p=0.606).

Relationships between OLHD performance and impairments (muscle function and confidence in
landing), in addition to OLHD performance and perceived disability, were investigated within the
ACLD and Control groups separately. Overall, poor to moderate non-significant relationships
were demonstrated except for a moderate to strong association between single-leg vertical jump
and hop distance performance within the Control group (r=0.68; p=0.0443) (see Appendix 9).

In summary, differences between ACLD and matched Controls in OLHD performance (hop
distance and transformed hop index scores) and isokinetic quadriceps strength (120° s⁻¹ and
180° s⁻¹) are strongly related. Differences between ACLD and matched Controls in OLHD
performance and perceived disability appear to be moderately related however, this finding may be only due to chance. Finally, differences between ACLD and matched Controls in OLHD performance and single-leg vertical jump performance and confidence in landing appear to have no association in this particular sample.
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<th>Differences between Controls - ACLD (matched Controls)</th>
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<th>Single Leg Vertical Jump</th>
<th>Confidence in Landing</th>
<th>ACL-QOL Score</th>
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<tr>
<td>Hop Distance</td>
<td>r = 0.37 &amp; p = 0.334</td>
<td>r = 0.69 &amp; p = 0.04</td>
<td>r = 0.77 &amp; p = 0.014</td>
<td>r = 0.04 &amp; p = 0.909</td>
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<td>Hop Index</td>
<td>r = 0.32 &amp; p = 0.408</td>
<td>r = 0.45 &amp; p = 0.225</td>
<td>r = 0.58 &amp; p = 0.103</td>
<td>r = -0.13 &amp; p = 0.736</td>
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<td>Hop Index (calculated from transformed data)</td>
<td>r = 0.48 &amp; p = 0.195</td>
<td>r = 0.75 &amp; p = 0.021</td>
<td>r = 0.70 &amp; p = 0.036</td>
<td>r = -0.11 &amp; p = 0.783</td>
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</table>

Table 15: Pearson Product Moment Correlation Coefficients (r-value) and corresponding level of significance (p-value) for the differences between ACLD and matched Controls in muscular function (isokinetic concentric quadriceps PT BW1 and single-leg vertical jump), confidence in landing, perceived disability (ACL-QOL questionnaire) and OLHD performance (hop distance and original and transformed hop index). Correlations deemed significant at the p<0.05 level are identified with an asterisk (*).
5.4.3 Contribution of take-off (muscular function) versus landing (confidence in landing) to OLHD performance

The contributions of take-off (mainly influenced by muscle function) versus landing (affected by fear of subluxation) to the horizontal distance achieved were explored by way of two modified versions of the OLHD within (ACLD) and between (ACLD versus Controls) groups. The first modified hop test was designed to assess the contribution of take-off whereby subjects hopped from one limb and landed on both whereas, the second modified hop test was developed to examine the contribution of landing whereby subjects hopped from both limbs and landed on one.

Differences within the ACLD (affected versus unaffected limbs) and between ACLD (affected and unaffected limbs) and their matched Controls for the variables: hop distance and confidence in landing for the two modified versions of the OLHD were tested using paired t-tests (Table 16).

A comparison of the mean hop distance achieved revealed no significant difference between the ACLD affected versus unaffected limbs, nor between the ACLD (affected and unaffected) and matched Controls, for either of the modified hop tasks.

While not significant, the mean differences in hop distance, between the ACLD limb and unaffected limbs of the ACLD and Controls, was 2 to 4 times greater in the second modified hop test compared to the mean differences in the first modified hop task. In other words, the ACLD demonstrated a greater difference in hop distance on their affected limb when compared to their unaffected limb and matched Controls in the modified hop, which isolated the landing phase. Thus, landing appears to be more of a challenge than take-off on the ACLD limb.
Analysis of the confidence in landing ratings demonstrated large significant differences between the ACLD affected and unaffected limbs, along with the ACLD affected and their matched Controls, in their performance of the second versus the first modified hop test. Namely, the ACLD were significantly less confident landing the hop test which isolated landing on their ACLD limb only when compared to landing on their unaffected limbs and their matched Controls.

In summary, no significant difference in hop distance was detected in either of the two modified OLHD tests upon comparing limb performance within the ACLD or between the ACLD and Controls (matched pairs). While not significant, the ACLD hopped less on their affected limb compared to their unaffected limb and matched Controls in the modified hop designed to isolate the landing phase. This implies that landing the OLHD could possibly be more of a challenge than take-off on the ACLD limb. The ACLD were considerably less confident in landing the modified OLHD which required them to take off from both limbs and land on the affected when compared to their unaffected limb and to their matched Controls.
Summary of the Hop Distance and Confidence in Landing Scores for the Two-Modified Hops for Distance

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<th>Modified Hop #2 -isolates Landing Phase</th>
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<td><strong>Difference in mean ± SEM (m)</strong></td>
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<td><strong>AACL- Unaffected Vs AACL-Affected</strong></td>
<td><strong>Mean ± SEM (0 to 1)</strong></td>
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<td>(n=10 pairs)</td>
<td><strong>p-value</strong></td>
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<td>1.92 ±0.08</td>
<td>9.42 ±0.30</td>
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<tr>
<td>1.95 ±0.06</td>
<td>8.93 ±0.40</td>
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<td><strong>AACL-Affected Vs Matched Control</strong></td>
<td><strong>Mean ± SEM (0 to 1)</strong></td>
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<tr>
<td>(n=9 pairs)</td>
<td><strong>p-value</strong></td>
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<td>1.97 ±0.07</td>
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</tr>
<tr>
<td>1.94 ±0.06</td>
<td>9.89 ±0.41</td>
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<tr>
<td><strong>AACL- Unaffected Vs Matched Control</strong></td>
<td><strong>Mean ± SEM (0 to 1)</strong></td>
</tr>
<tr>
<td>(n=9 pairs)</td>
<td><strong>p-value</strong></td>
</tr>
<tr>
<td>1.95 ±0.08</td>
<td>9.36 ±0.33</td>
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<td>1.95 ±0.08</td>
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<td>1.88 ±0.06</td>
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<tr>
<td>2.04 ±0.08</td>
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</tr>
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<tr>
<td>2.03 ±0.09</td>
<td>0.01 ±0.09</td>
</tr>
</tbody>
</table>

**Table 16** Summary of the means (±SEM), mean differences between Controls and AACL-matched pairs (±SEM) and p-values for the hop distance and confidence in landing scores for the two modified hops described. Mean differences were assessed using paired t-tests except for the mean differences in confidence in landing modified hop #1 between AACL unaffected and affected limbs, in addition to the AACL unaffected and their matched Controls, which failed the test of normality therefore, a Wilcoxon Signed Rank Test was employed (−). Mean differences were found significant (•) at the p<0.05 level.
CHAPTER 6
DISCUSSION

The hypothesis that the OLHD scores can differentiate between populations, but not necessarily individuals, was supported by the results of this study. The ACLD group demonstrated significantly lower hop distance scores on their injured limb as well as significantly poorer hop index scores, compared to healthy, non-injured Controls. However, upon exploring the percentage of ACLD subjects with an abnormal hop index according to the established reference norms, the sensitivity is low. Controlling for differences in inherent athletic ability and leg dominance had no impact on the diagnostic ability of the hop index scores.

An examination of the hop distance and hop index scores revealed that the distance hopped on the non-injured (the referent) limb is a critical factor with respect to the sensitivity of the hop index in the ACLD sample. Therefore, a method to minimize the effect of the arithmetic variation of the proportional differences was proposed in order to improve the sensitivity of the hop index in the assessment of ACL injuries.

Furthermore, it had been hypothesized that the ACLD would demonstrate impaired muscular function and a fear of subluxation on landing the OLHD and that these impairments could be possible causes of a reduction in OLHD performance. Results demonstrated that the ACLD muscle function (isokinetic concentric quadriceps strength and single-leg vertical jump height) was impaired and that the ACLD were less confident in landing the OLHD compared to matched Controls. The difference found between the ACLD and matched Controls muscular strength was negligible relative to the differences found between their OLHD performance and particularly their confidence in landing. While a loss in ability to hop was associated with a
decline in muscular strength (isokinetic concentric quadriceps PT BWt⁻¹) secondary to ACL injury, no relationships were found between OLHD performance and confidence in landing.

Finally, the ACLD perceived themselves to be significantly disabled relative to matched Controls (as defined by the ACL-QOL questionnaire). The ACLD differed greatly from matched Controls in their perceptions of disability compared to the observed differences in their OLHD performance. Relationships between OLHD performance and perceived disability do not appear to be strongly related.

6.1 SUBJECT DESCRIPTION

The mean Modified Knee Scoring Scale of Lysholm score for the ACLD of this study (mean ±SD= 80.3 ±10.69) were similar to mean scores reported within the literature for individuals with objective knee instability (75.6 ±17.8) [124] and individuals with ACLD knee beyond the acute stage of injury (81.1) [125].

The mean Tegner Activity scores demonstrated that the ACLD and Controls were comparable in terms of their athletic participation levels, at the time of testing. However, a comparison of the ACLD pre- and post-injury Tegner Activity scores revealed that the ACLD engaged in significantly less demanding activities upon injuring their ACL. This reduction in the participation of more challenging athletic activities was presumably due to their knee condition. There was no difference in Lysholm scores between the ACLD individuals who took part in recreational or competitive sporting activities versus those who pursued activities of daily living only. This finding minimizes the possibility of high Lysholm scores as a result of a restricted activity level.

In terms of the overall IKDC grade, the ACLD patients were graded as having an Abnormal (C) or a Severely Abnormal (D) knee profile. These grades are consistent with Synder-Mackler et al.
(1997) who found ratings of C and D in ten ACLD patients requiring surgical reconstruction; however, they also found overall ratings of C and D in ten ACLD patients who were able to return to all sporting activities. Therefore, it would appear that the discriminative ability of the IKDC between those requiring surgery versus those able to return to previous sporting activities is poor [113].

Anthropometrically, the ACLD were heavier (BMI greater by 9%) and more muscular (FFM greater by 14%). Evaluation of waist girth and BMI scores against the CPAFLA Health Benefit Zones [74] revealed that all subjects had a healthy waist girth, while 70% of the ACLD (n=7) and 10% of the Controls (n=1) demonstrated a borderline unhealthy BMI. However, this latter finding is attributed to a higher degree of lean body mass and not a high percentage of body fat. Although the ACLD and Controls differ with respect to their lean body mass, the comparability of the two groups with respect to the OLHD has been confirmed (see Section 5.2).

The chronicity of injury within the given ACLD sample varied from 5.3 to 60 months. The time post injury may have had an effect on the measures of impairment, functional limitations and perceived disability. However, an assessment of the effect of chronicity was not possible due our small sample size.

6.2 OLHD SCORES

6.2.1 Differentiating Between Populations

6.2.1.1 Hop Distance Scores

Our ACLD hop distance scores (Table 9) were similar to those reported in studies which employed a similar protocol (Table 4). In addition, our Controls hopped as far as the healthy, non-injured population reported by Tegner et al. (1986) who employed the same protocol and score calculation [118] (Table 4). In the present study the ACLD subjects hopped significantly
less than Controls by 12% (Table 9) similar to results published by Tegner et al. (1986) who demonstrated an 18% difference between ACLD and Controls hop distance scores [118] (Table 4).

6.2.1.2 **Hop Index Scores**

In comparing our results to those cited within the literature, the mean hop index scores of our ACLD and Control group (Table 9) were basically as symmetrical, if not more symmetrical than published results [9, 106, 118, 119] (see Table 5). In contrasting the hop index scores of the ACLD and Controls of the present study, the ACLD had a significantly greater asymmetrical hop index relative to Controls (9% difference) which is consistent with results within the literature (6 and 18% difference) [9, 118] (Table 5).

6.2.1.3 **Impact of Correcting for Differences in Inherent Athletic Ability and Leg Dominance on OLHD Scores**

Controlling for differences in inherent athletic ability and the impact of leg dominance was carried out in an attempt to increase the difference in OLHD performance between the ACLD and matched Controls. The separation between the ACLD and Controls increased substantially upon controlling for differences in inherent athletic ability; however, controlling for leg dominance had no impact (Figure 5). Thus, when using the hop distance to differentiate between the given samples, correcting for differences attributed to natural variation in hop performance is important to ensure differences found are due to the ACL injury alone. Whereas, correcting for leg dominance had no impact in the ability to differentiate between the samples.

With respect to the hop index, controlling for differences in inherent athletic ability and leg dominance had minimal to no impact on increasing the separation between ACLD and Controls.
Consequently, when using the hop index score to differentiate between the given samples, controlling for these two factors was not beneficial.

### 6.2.2 Differentiating Between Individuals

Comparing the percentage of subjects in the abnormal versus normal hop index categories in the present study to results cited within the literature, the percent probability of detecting an abnormal hop index in our group of ACLD patients (sensitivity) (Table 12) was lower than published results (Table 7). However, the percent probability of detecting a normal hop index in our Control group (specificity) (Table 12) was as high as those cited in the literature (Table 7).

The usefulness of a diagnostic test is assessed via the sensitivity and specificity rates. The closer that these statistical indexes are to 100%, the more accurate the diagnostic tool [148]. In our study, the sensitivity ranged from 20 to 50% whereas, the specificity was 100% (Table 12) which implies that the OLHD is poor at identifying the presence of a lower limb problem but good at identifying normalcy. Its limited ability to discriminate between individuals with an ACLD knee versus non-injured individuals is consistent with similar published works [9, 13].

Upon observation of the distribution of the hop distance scores it became evident that the variation in the distance achieved on the injured limb of the ACLD was less than that of the non-injured limbs of the ACLD and Controls (Figure 8). This finding led us to believe that the ACLD performed similarly on their injured limb regardless of the hop distance achieved on their non-injured limb. Consequently, the hop distance on the non-injured limb was a critical factor in the sensitivity of the hop index in the assessment of ACL injuries. Correlational analyses conducted between hop distance scores and hop indexes in the ACLD and Control groups separately confirmed our theory.
There was no association between the hop distance and hop index within the Controls since all of the Controls demonstrated limb symmetry irrespective of actual distance hopped (Figure 9). Furthermore, the distance achieved on the ACLD limb had nothing to do with the hop index score as there was no association between distance hopped and hop index score on the injured limb (Figure 11). On the contrary, the ACLD demonstrated a moderate to strong correlation between the hop distance achieved on the non-injured limb and the hop index (Figure 10). Therefore, the farther the ACLD patients hopped on the non-injured limb, the poorer the hop index. Conversely, the shorter the distance hopped on the non-injured limb the better the hop index. As a result, it was deemed important to control for the differences in variation in hop distance scores between the injured and non-injured limbs to ensure that the distance hopped on the non-injured limb became less of a critical factor in the sensitivity of the hop index score.

Data transformations are useful in rectifying certain irregularities of a particular data set in order to ensure that the underlying assumptions of many statistical methods are satisfied [145]. Although a significant difference in the hop distance score distributions between the injured versus non-injured limbs did not exist, a data transformation was justified on the basis that the outcome was one of prediction and not statistical inference (B. Kirshner, personal communication, September 13, 2001).

The choice of a transformation to equalize the variance between data sets is dependent upon how much the standard deviation increases with the increasing mean. For instance, the logarithmic transformation is appropriate if the standard deviation increases in proportion to the mean. While the reciprocal transformation is suitable if the standard deviation is proportional to the mean squared. Whereas, the square root transformation is recommended if the standard deviation is proportional to the square root of the mean [145].
In the present study, the standard deviation increased approximately in proportion to the mean upon comparing the standard deviation relative to the mean for the hop distance scores of the ACLD limb versus the non-injured limbs of the ACLD and Controls (Table 17).

<table>
<thead>
<tr>
<th>HopDistance (m)</th>
<th>ACLD Injured</th>
<th>Non-Injured</th>
<th>Controls Non-Dominant</th>
<th>Controls Dominant</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>1.58</td>
<td>1.72</td>
<td>1.78</td>
<td>1.75</td>
</tr>
<tr>
<td>s.d.</td>
<td>0.12</td>
<td>0.18</td>
<td>0.20</td>
<td>0.17</td>
</tr>
<tr>
<td>s.d. / mean</td>
<td>0.08</td>
<td>0.10</td>
<td>0.11</td>
<td>0.10</td>
</tr>
</tbody>
</table>

**Table 17** Summary of the mean, standard deviation (s.d.) and the s.d. expressed relative to the mean (s.d. / mean) for the hop distance scores of the ACLD (injured and non-injured limbs) in addition to the Controls (non-dominant and dominant limbs).

Therefore, a logarithmic transformation was used to equalize the standard deviations among the hop distance scores of the injured limbs of the ACLD and the non-injured limbs of the ACLD and Controls. The original hop distance scores of the ACLD limb demonstrated a lower mean and less variability compared to the non-injured limbs of the ACLD and Controls (Table 18). Whereas, the transformed hop distance scores of the ACLD limb demonstrated a lower mean but similar variance compared to the non-injured limbs of the ACLD and Controls (Table 18).

<table>
<thead>
<tr>
<th>HopDistance (m)</th>
<th>Original Injured</th>
<th>Original Non-Injured</th>
<th>Logged Injured</th>
<th>Logged Non-Injured</th>
<th>Original Controls Non-Dominant</th>
<th>Original Controls Dominant</th>
<th>Logged Controls Non-Dominant</th>
<th>Logged Controls Dominant</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>1.58</td>
<td>1.72</td>
<td>0.20</td>
<td>0.23</td>
<td>1.78</td>
<td>1.75</td>
<td>0.25</td>
<td>0.24</td>
</tr>
<tr>
<td>s.d.</td>
<td>0.12</td>
<td>0.18</td>
<td>0.03</td>
<td>0.04</td>
<td>0.20</td>
<td>0.17</td>
<td>0.05</td>
<td>0.04</td>
</tr>
</tbody>
</table>

**Table 18** Summary of the mean and standard deviation (s.d.) of the original and log_{10} transformed scores of the ACLD (injured and non-injured) as well as the Controls (dominant and non-dominant).
As depicted in Figure 24, the logarithmic transformation results in equalizing the standard deviations by way of spreading out the hop distance scores with smaller values and compressing the larger values [145, 146].

Figure 24  Summary of the absolute distances hopped (m) on the non-dominant and dominant limbs of the Controls and the injured and non-injured limbs of the ACLD using a) a linear scale and b) a logarithmic scale. Note that the logarithmic scale has been labeled in the original units.

Transformation of the hop distance scores permitted a recalculation of the hop indexes without concern for the differences in arithmetic variation of the proportional differences (Table 13). Upon comparison of the hop indexes recalculated using the transformed versus original hop distance scores, the separation between the ACLD and Controls increased (Figure 13). Furthermore, comparing the distribution of the hop indexes calculated from the original versus transformed hop distance scores unveiled an increase in the percentage of ACLD patients with an abnormal hop index. More specifically, the percentage of ACLD classified as having an abnormal hop index increased from 20 to 60% using the reference norm (normal hop index > 85%) defined by Barber et al. (1990) [9] and from 50 to 70% using the reference norm (>90%) according to Daniel et al. (1982 and 1988) [105, 115]. Whereas the percentage of Controls who demonstrated a normal hop index basically remained unchanged (Table 19).
Sensitivity and Specificity of the Hop Index in the Assessment of ACL Injuries
using the Original and Transformed Hop Index Scores

Table 19 summaries the % of tests that yielded abnormal results in the ACLD, % of tests that demonstrated a normal hop index in the Controls, % of tests that demonstrated a normal hop index in an ACLD and the % of tests that demonstrated an abnormal hop index in Controls for hop index scores calculated from a) the original and b) the transformed (log_{10}) hop distance scores.

Therefore, transformation of the hop distance scores prior to calculating the hop index within the ACLD male sample improved the sensitivity of the hop index in the assessment of ACL injuries.
6.3 VARIATIONS BETWEEN ACLD AND CONTROLS IN IMPAIRMENTS AND PERCEIVED DISABILITY

6.3.1 Measures of Muscular Function

6.3.1.1 Isokinetic Concentric Quadriceps Strength

In the present study, there were no significant differences found in isokinetic concentric quadriceps strength at any of the given test velocities in the non-injured leg of the ACLD when compared with matched Controls. This implies that the Control group can be used adequately as a reference guide with respect to dynamometric measurement of lower limb strength.

With respect to the ACLD limb, isokinetic muscle function testing demonstrated a mean concentric quadriceps strength deficit compared to matched Controls at all test velocities. However, while the difference in isokinetic quadriceps strength at 60 and 180° s\(^{-1}\) were approaching significance (p=0.062 and 0.095, respectively), the only statistically significant deficit in quadriceps strength between the ACLD and their matched Controls was found was at 120° s\(^{-1}\) (p=0.035) (Table 14).

Examination of the individual strength scores revealed that four of the ACLD subjects demonstrated a strength deficit on their non-involved limb when compared to their involved limb. However, whether their quadriceps strength was actually greater on the injured side or whether it only appeared so (due to a poor performance on the non-involved limb) is difficult to assess from the raw scores alone. Therefore, the expected decline in PT with increasing velocity [89] was determined from our Control data to enable a comparison of the observed percent decline in the involved and non-involved limbs of the four ACLD subjects in question. Results demonstrated a decline in PT of 30.6% with increasing speed from 60 to 180° s\(^{-1}\) for the dominant and non-dominant limbs in the Controls. In comparison, the decline was greater (37
to 48%) on the non-injured limb in all 4 ACLD subjects and less (19 and 23%) on the involved limb in two of the four ACLD subjects for unknown reasons.

Nevertheless, the deficit in quadriceps strength in the ACLD found in the present study is consistent with results within the literature that evaluated isokinetic concentric quadriceps strength differences between the injured limb and non-injured limb within an ACLD population [84-86].

Studies conducted to compare normative data using different (reliable) isokinetic systems have determined that results are dynamometer specific [89, 103, 104]. Normative PT knee flexion and extension values using the Lido Active system have been reported by Lord et al. (1992). However, these investigators reported the combined gender scores only, which limits the value in comparing this normative data to results of the present study.

6.3.1.2 Single-Leg Vertical Jump

Upon comparing the mean single-leg vertical jump score of our Control group (Table 14) to published works (Table 2), it appears that our Controls hopped slightly less. The difference in height achieved is likely due to the differences in jump protocols pertaining to the use of the arms. In the present study we restricted arm swing in order to better assess the contribution of the leg extensors as the use of the arms has been shown to increase jump height by 6 to 40% [99].

Comparison of the single-leg vertical jump scores of our ACLD sample (Table 14) to published studies (Table 2) demonstrates similar results. However a direct comparison and interpretation is difficult due to differences in sample populations (genders combined) and jump protocols (arm swing versus no arm swing). In the present study the ACLD subjects jumped significantly less
high compared to Controls (18.5%) (Table 14). Similarly, Barber et al. (1990) demonstrated a 13% difference between an ACLD and healthy, non-injured population for single-leg vertical jump scores [9] (Table 2).

The ability of the single-leg vertical jump index to differentiate between ACLD and their matched Controls in the present study was poor relative to the OLHD (Figure 19). The greater variability in jump index scores (mean ±SD: ACLD= 89.4 ±18.1%; Controls=103.5 ±14.2%, p=0.047) relative to the original hop index scores (ACLD= 90.9 ±2.2%; Controls=98.9 ±1.5%, p=0.002) makes the single-leg vertical jump test less desirable for discriminating between the given samples. These findings are consistent with results published by Barber et al. (1990) who also found a large standard deviation in the single-leg vertical jump index in a healthy, non-injured population (105 ± 22%) which they could not attribute to a particular sports activity group or gender [9].

6.3.2 Confidence in Landing

To date, there are no published studies that have evaluated the ACLD population’s confidence in landing a specific functional task. As expected, the results of the present study demonstrated that the Controls were remarkably confident in landing the OLHD on both the dominant and non-dominant limbs. While the ACLD were equally confident to Controls on their non-injured limb, they reported significantly less confidence in landing the OLHD on their ACLD limb (Table 14).

6.3.3 Perceived Disability

In the present study, the ACL-QOL scores of the ACLD subjects reflect that they perceived themselves to be significantly more disabled than their matched Controls (Table 14). Currently normative data pertaining to the ACL-QOL does not exist. However, our ACLD scores are similar to published results. Mohtadi (1998) demonstrated that the ACL-QOL questionnaire was
able to discriminate between those who underwent surgery (average score of 31) versus those who underwent conservative treatment (average score of 79). Of the 36 ACLD individuals who went on to have surgery only four demonstrated a score greater than 50 out of 100 whereas of the 14 ACLD individuals that were treated conservatively, only one had a score less than 50 [127]. Similarly, all of the ACLD subjects within the present study went on for surgery (mean score of 42) and out of a total of 10, only two demonstrated a score greater than 50.

6.4 VARIATIONS BETWEEN ACLD AND CONTROLS IN IMPAIRMENTS AND PERCEIVED DISABILITY RELATIVE TO OLHD PERFORMANCE

Measures of impairment, function and perceived disability specific to the ACLD population provide important information regarding the status of the ACL injured individual. In the present study, the ACLD demonstrated weaker concentric quadriceps strength, a reduction in their ability to jump vertically, an impaired OLHD performance, reported less confidence in landing the OLHD, and perceived themselves to be more disabled relative to Controls. However, the ability of these various measures to discriminate between ACLD versus healthy, non-injured individuals varied (Figure 19). Based on the negligible differences found between the ACLD and matched Controls in strength measures, we need to rely more heavily on functional measures, such as the OLHD hop index (transformed) scores in our objective assessments. In addition, self-report assessments such as confidence in landing and ACL-QOL score have proven to distinguish between the ACLD and Controls in a highly reliable manner and provide valuable insights into the individuals emotional function and perceived disability.
6.5 RELATIONSHIPS BETWEEN MUSCULAR FUNCTION, CONFIDENCE IN LANDING, PERCEIVED DISABILITY AND OLHD PERFORMANCE SECONDARY TO ACL INJURY

Impaired muscular function and a fear of subluxation on landing the OLHD have been considered possible causes of a reduction in OLHD performance in the ACLD population [105, 106]. To determine the extent of their association, measures of strength and confidence in landing were correlated to OLHD performance.

Several investigators have demonstrated a positive correlation between isokinetic concentric quadriceps PT and OLHD [13, 129-132]. However, there is no consensus regarding the extent to which isokinetic strength and hop performance are associated due to differences in data analysis strategies, samples, knee pathology, equipment, isokinetic parameters and testing methodology.

The poor and non-significant correlations that were found between isokinetic quadriceps strength and OLHD performance in both the Controls and ACLD within this study is likely a consequence of our small sample size in addition to the small range in scores. However, differences between ACLD and their matched Controls in OLHD performance (hop distance and transformed hop index scores) and isokinetic concentric quadriceps strength at 120 and 180° s⁻¹ were strongly related. Therefore, a loss in ability to hop is associated with a reduction in isokinetic quadriceps strength as a result of ACL injury.

The height achieved in the performance of the single-leg vertical jump demonstrated a moderate to strong association to the horizontal distance achieved in the OLHD (r = 0.68; p = 0.0443) within our Control group. However, there was no association found between the single-leg vertical jump and OLHD on the ACLD limb nor was a relationship detected between the differences in the ACLD and their matched Controls with respect to single-leg vertical jump and
OLHD. These findings may be a consequence of our small sample, limited range in scores and the landing requirements between these two functional tasks. The OLHD may present as more of a challenge to the ACLD compared to the single-leg vertical jump since knee instability is more likely to be provoked on landing the OLHD due to the capsuloligamentous sagittal load [106, 119, 135]. There were no studies found within the literature that explored the relationship between the single-leg vertical jump and OLHD performance therefore, we were unable to confirm or disprove our findings.

In addition to muscular function, confidence in landing was proposed as a possible determinant of OLHD performance. There was no relationship found between confidence in landing and OLHD performance within the ACLD or Controls. Furthermore, differences between ACLD and matched Controls in confidence in landing and differences between their OLHD performance were not related. Given that the ACLD demonstrated a wide range of confidence in landing scores (0.85 to 10), it appears that there is no association between OLHD performance and confidence in landing this task within the ACLD. To date there are no published studies that have explored confidence in landing as a determinant of OLHD performance therefore, whether these associations hold true for a larger sample remains unknown.

To further assess the impact that muscular function and confidence in landing has on hop performance, two modified versions of the OLHD, designed to assess the contribution of take-off (influenced by muscular function) versus landing (affected by the fear of subluxation) were explored. Results demonstrated that the ACLD lacked confidence in landing the modified hop test, which isolated landing on their ACLD limb. However, there was no significant difference in hop distance upon comparing limb performance within the ACLD or between the ACLD and Controls (matched pairs) in either of the modified hop tests. While not significant, a greater difference in hop distance between the ACLD limb and the unaffected limbs of the ACLD and
matched Controls in the modified hop designed to assess the contribution of landing was observed. This may imply that landing is more of a challenge than take-off on the ACLD limb. The lack of a significant finding in the differences in mean hop distance may have been due to fact that both the challenge of take-off and landing on the ACLD limb are required in order to demonstrate a noticeable reduction in the ability to hop for distance.

In addition to exploring determinants of the OLHD, an assessment of perceived disability (ACL-QOL questionnaire) and its association with OLHD was investigated. Results demonstrated that the ACLD and Controls ACL-QOL scores were not associated with OLHD performance. Differences between ACLD and matched Controls in perceived disability versus differences in OLHD performance (hop distance and transformed hop index scores) were moderately related ($r=0.44$) although this finding may have been due to chance ($p=0.231$). Again, due to our small sample size and the narrow range in scores conclusive evidence regarding the relationships between OLHD performance and perceived disability within the ACLD is lacking.

To date, there are no published studies that explore the relationship between perceived disability, as defined by the Mohtadi's ACL-QOL score, and OLHD performance in an ACLD population. However, recently published results demonstrated a poor to moderate correlation between patient's QOL score and hop performance ($r=0.37; p=0.014$) in 60 ACLR patients one year post surgery [128]. Therefore, it would appear that patients (ACLD and ACLR) perceived disability is not strongly related to their OLHD performance. Nonetheless, it may be unrealistic to expect a high association between a specific test of lower limb function and a tool used to assess overall quality of life consequently, even moderate associations may have clinical importance (T. Birmingham, personal communication, September 13, 2001).
Correlating the differences between ACLD and matched Controls in hop distance and transformed hop index scores to the differences between ACLD and matched Controls in the various measures of impairment and perceived disability demonstrated similar results. Whereas, correlations pertaining to the differences in the original hop index scores and the differences in muscular function, confidence in landing and perceived disability differed. Therefore, assessment of the relationships between impairments, perceived disability and OLHD performance further substantiated the need to transform the hop distance scores prior to computing the hop index.

In summary, our ACLD subjects demonstrated significantly lower hop distance scores on their injured limb as well as significantly poorer hop index scores, compared to healthy, non-injured Controls which is consistent with results cited within the literature [9, 118]. However, upon exploring the percentage of ACLD subjects with an abnormal hop index (according to the established reference norms) our sensitivity rates in detecting an abnormal hop index in the ACLD were as low, if not lower, than published works [9, 13]. However, this study was the first to assess the limitations of the hop index score as a diagnostic tool and the first to propose a method to improve the sensitivity of the hop index score in its detection of lower limb functional limitations in the ACLD.

Assessment of impairments in the ACL-injured demonstrated deficits in muscular function (isokinetic concentric quadriceps strength and single-leg vertical jump height) similar to studies within the literature [9, 84-86] and a lack of confidence in landing which has not been formally investigated prior to this study. A loss in ability to hop was associated with a decline in muscular strength (isokinetic concentric quadriceps PT BWt\(^{-1}\)) secondary to ACL injury whereas, no relationships were found between OLHD performance and confidence in landing.
Furthermore, evaluation of the ACLD perceptions of disability using Mohtadi's ACL-QOL questionnaire demonstrated comparable scores to work by Mohtadi (1998), who was able to discriminate between an ACLD sample who were treated conservatively versus those requiring surgery [127]. The relationship between the ACL-QOL assessment and OLHD performance demonstrated that perceived disability does not strongly reflect OLHD performance in our ACLD sample, which is, similar to published findings in an ACLR population [128].
CHAPTER 7

CONCLUSIONS

Hop Index: Descriptive Ability-
1) The hop index discriminates between an ACLD and healthy, non-injured sample
2) Correcting for differences in inherent athletic ability and leg dominance did not improve the separation between the given samples

Hop Index: Diagnostic Ability-
3) The ability to discriminate among ACLD individuals (sensitivity) is poor
4) The distance hopped on the non-injured limb within the ACLD is a critical factor in the sensitivity of the hop index
5) A logarithmic transformation of the hop distance scores improves the sensitivity of the hop index in the ACLD

OLHD: Determinants of Performance and Association to Perceived Disability-
6) A decline in muscle function (isokinetic concentric quadriceps strength) was associated with a decline in the ability to hop on the ACLD limb
7) Confidence in landing and perceived disability were not associated with OLHD performance
In conclusion, the OLHD is able to discriminate between an ACLD sample (who went on to have surgery) and a healthy, non-injured sample upon comparison of the mean differences in hop distance and hop index scores.

Differences in inherent athletic ability and the impact of leg dominance were both identified as possible limitations in the ability of the OLHD scores to distinguish between an ACLD and healthy, non-injured population. Correcting for differences in inherent athletic ability improved the discriminative ability of the hop distance scores however, correcting for leg dominance had no impact. Regarding the hop index score, correcting for differences in inherent athletic ability and leg dominance did not improve the separation between the given samples.

The preceding results imply that the OLHD scores reliably distinguish between an ACLD and healthy, non-injured sample. However, the percentage of ACLD subjects with an abnormal hop index (20%-50%) and the percentage of Controls with a normal hop index (100%) indicates that the OLHD is poor at identifying the presence of a lower limb problem but good at identifying normalcy.

Differences in inherent athletic ability and the impact of leg dominance were not factors in the sensitivity of the hop index in the detection of lower limb functional limitations when categorizing a hop index as either normal or abnormal according to the established reference norms. However, an analysis of the hop distance scores for the injured and non-injured limbs of the ACLD, and the dominant and non-dominant limbs of the Controls, revealed less variation in hop performance on the ACLD limb. Therefore, the farther the ACLD subjects hopped on their non-injured limb, the poorer their hop index making the distance hopped on the non-injured limb a critical factor in the sensitivity of the hop index in the given ACLD sample. Based on these findings, a data transformation was warranted to minimize the effect of the arithmetic variation of
the proportional differences in an attempt to improve the sensitivity of the hop index in the assessment of ACL injuries.

The choice of transformation is based on the behavior or distribution of the hop distance scores. Given that the standard deviation of the hop distance scores of the ACLD limb increased approximately in proportion to the mean of the non-injured limb, the logarithmic transformation became the transformation of choice [145]. This transformation equalizes the standard deviations by way of spreading out the hop distance scores with smaller values and compressing the larger [145, 146].

Transformation of the hop distances enabled a recalculation of the hop index scores without concern for the differences in variation of the underlying hop distance scores. The distribution of the hop indexes calculated from the transformed hop distance scores demonstrated an increase in the percentage of ACLD patients with an abnormal hop index compared to the original hop index scores. In fact, the percentage of ACLD classified as having an abnormal hop index increased from 20 to 60%, using the reference norm defined by Barber et al. (1990) [9], and from 50 to 70% using the reference norm according to Daniel et al. (1982 and 1988) [105, 115]. The percentage of Controls who demonstrated a normal hop index basically remained unchanged. Therefore, transformation of the hop distance scores prior to calculating the hop index within the ACLD sample, improved the sensitivity of the hop index in the assessment of ACL injuries.

However, in view of the fact that all ACLD subjects within the present study went on to have ACL reconstructive surgery, we would have expected greater than the 60 to 70% that demonstrated an abnormal hop index upon transforming the hop distance scores. Therefore, the need to investigate whether our findings in the present study hold in a larger sample is
critical prior to recommending the use of the logarithmic transformation to improve the sensitivity of the hop index in the assessment of ACL injuries within a clinical setting.

In theory, the OLHD was designed to assess both strength and confidence/stability in the involved leg [105, 106]. In the present study, the ACLD demonstrated impaired muscular function (weaker concentric quadriceps strength and a reduction in leg extensor power assessed via the single-leg vertical jump) and reported less confidence in landing the OLHD relative to matched Controls. With respect to the possible determinants of OLHD performance, a loss in ability to hop was associated with a decline in muscular strength (isokinetic concentric quadriceps PT BW$^{-1}$) secondary to ACL injury. However, no relationships were found between OLHD performance and confidence in landing.

In addition to exploring determinants of the OLHD, an assessment of perceived disability (Mohtadi’s ACL-QOL questionnaire) and its association with the OLHD was investigated. Results demonstrated that perceived disability is not strongly associated with OLHD performance within the ACLD.

The measures of impairment, function and perceived disability investigated within this study differed in their ability to discriminate between ACLD versus healthy, non-injured individuals. Separation between the ACLD and matched Controls in the strength measures was negligible relative to the separation found between groups in terms of their transformed hop index scores, reported confidence in landing and perceived disability. These findings emphasize the need to rely more heavily on functional measures such as the OLHD and self-report assessments, versus measures of strength, in our objective assessments of the ACLD sample. However, while the self-report measures separated the ACLD and Controls in an even more highly reliable
manner and provide valuable insight into the perceptions of the injured athlete, they do not appear to be strongly related to function.
CHAPTER 8
FUTURE DIRECTIONS

Further research is required to investigate whether the diagnostic ability of the hop index, in the detection of functional limitations in the ACLD, improves upon transformation of the hop distance scores in a larger population across the spectrum of injury, with varying levels of chronicity [134]. This is critical prior to recommending the use of the logarithmic transformation to improve the sensitivity of the hop index in the assessment of ACL injuries within a clinical setting. Furthermore, consideration should be given to employing Receiver Operator Characteristic Curve in order to select an appropriate cut-off point in the determination of a normal versus abnormal hop index in the ACLD versus non-injured, healthy population.

In addition to the diagnostic ability, the usefulness of the OLHD should be further assessed with respect to specific applications pertaining to prognosis and responsiveness to treatment [134] in light of the findings of this study. To determine the prognostic validity of the OLHD, the relationship between the hop index post injury and the long-term outcome (e.g., the ability to return to pre-injury sporting activities, frequency of giving way episodes and/or the need for ACL surgical reconstruction) should be investigated [134].

The approach in validating the hop index with respect to its responsiveness to treatment should involve a determination of the within-patient change in hop distance scores, with either conservative or surgical intervention, in relation to the expected changes in other relevant measures assessed prospectively [134].

Further exploration regarding the relationships between OLHD performance and muscular function, confidence in landing and other possible impairments is warranted in a larger sample
to provide more conclusive evidence regarding their associations within the ACLD population. Identifying and investigating all possible determinants of OLHD performance will enable researchers and clinicians to clinically isolate the defective component to ultimately optimize lower extremity function in the ACLD population.

Although not part of this thesis, kinematic data pertaining to the OLHD within the ACLD and healthy, non-injured Controls was gathered and an analysis of this data will be undertaken in order to identify and define the ACLD's adaptations during their performance of this lower extremity functional test.

In the event that the sensitivity of the OLHD proves to be sub optimal in a larger sample of ACLD individuals who report functional limitations secondary to knee instability, consideration should be given to the development of a more challenging lower limb functional test in the assessment of ACL injuries. The test of choice must be objective, reproducible and reliable. It should provide an independent assessment of limb performance such that the opposite limb can be used for comparison. Finally, it ought to simulate stresses about the knee encountered during activities relevant to the athlete, stress in multiple planes of motion and incorporate 'reactive' testing.
REFERENCES


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Appendix 1
# SUBJECT INCLUSION AND EXCLUSION CRITERIA

<table>
<thead>
<tr>
<th>HEALTHY NON-INJURED CONTROLS</th>
<th>ACLD SUBJECTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inclusion Criteria</strong></td>
<td><strong>Inclusion Criteria</strong></td>
</tr>
<tr>
<td>• Males 18 to 42 years of age</td>
<td>• Males 18 to 42 years of age</td>
</tr>
<tr>
<td>• Good health status</td>
<td>• Good health status</td>
</tr>
<tr>
<td>• Grade 2 or 3 ACL ligamentous laxity on manual testing</td>
<td>• Grade 2 or 3 ACL ligamentous laxity on manual testing</td>
</tr>
<tr>
<td>• Complete ACL tear (confirmed arthroscopically post testing)</td>
<td>• Complete ACL tear (confirmed arthroscopically post testing)</td>
</tr>
<tr>
<td>• At least 6 weeks post ACL injury</td>
<td>• At least 6 weeks post ACL injury</td>
</tr>
<tr>
<td><strong>Exclusion Criteria</strong></td>
<td><strong>Exclusion Criteria</strong></td>
</tr>
<tr>
<td>• History of low back pain</td>
<td>• History of low back pain</td>
</tr>
<tr>
<td>• Lower limb joint problems/pain</td>
<td>• Lower limb joint problems/pain other than involved knee</td>
</tr>
<tr>
<td>• Abnormal limb symmetry index (&gt; 15% difference between limbs)</td>
<td>• Multi-ligamentous laxity of the involved knee</td>
</tr>
<tr>
<td>• Unwillingness to fast for 6 hours prior to testing (caffeinated beverages not permitted) or moderate to strenuous exercise 48 hours prior to testing</td>
<td>• Unwillingness to fast for 6 hours prior to testing (caffeinated beverages not permitted) or moderate to strenuous exercise 48 hours prior to testing</td>
</tr>
</tbody>
</table>
Appendix 2
CONSENT TO PARTICIPATE IN A RESEARCH STUDY

Determinants of One-Leg Hop Performance in the Anterior Cruciate Ligament (ACL) Deficient Population

You are invited to partake in a research study at the Orthopaedic and Arthritic Campus of Sunnybrook & Woman's College Health Science Center. It is the intention of our research to determine possible causes for a difference in performance, between the injured versus non-injured limb, during the one-leg hop for distance in the ACL deficient population. This consent form is to help you make a well-informed decision about participating in this study.

Background Information
The one-leg hop for distance is a performance test often administered by clinicians to evaluate an individual's function after a knee ligament injury. In the event that this test detects abnormal limb symmetry, the individual with an ACL-deficiency is considered to have significant limitations in sporting activities. However, this test cannot determine which of the several components of an individual's function is problematic. In this study we will assess an individual's muscular strength and confidence in landing and explore how these two mechanisms influence an individual's performance of the one-leg hop for distance. A better understanding of the functional changes that result from an ACL injury is essential in refining post injury rehabilitation in order to optimize knee function.

Description of Study
To participate in this study, you would come to our hospital on one occasion only, for approximately 2 hours. During your visit, you will participate in a brief interview, complete questionnaires and engage in various functional and strength measures. You will be asked to bring and wear a pair of cycling shorts, a T-shirt and training shoes for the testing. The session will be organized as follows:

1) A brief medical history to determine whether you are eligible for the study.
2) Body composition measurements including: height, weight, leg length, percentage of body fat using bioelectrical impedance, waist girth. Knee measurements including knee swelling and range of motion.
3) A warm-up on a stationary bike for 5 minutes.
4) Strength testing using the leg press.
5) A knee function questionnaire.
6) Single-leg vertical jump will be performed three times on each leg.
7) One-leg hop for distance (taking off and landing on the same leg) will be performed three times on each leg. A confidence in landing scale will be administered before the test trials.
8) An activity level questionnaire.
9) Two variations of the one-leg hop for distance will be performed three times on each leg. Again, a confidence in landing scale will be administered before the test trials.
10) Quality of life assessment questionnaire.
11) Isokinetic muscular strength testing of the knee musculature.
**Risks and Benefits**

The risks involved in this study are: 1) the possibility of experiencing symptoms of knee instability or pain upon landing from either the single-leg vertical jump or the one legged hop for distance and 2) residual muscle soreness from the strength, single-leg vertical jump and one-leg hop for distance measures. You will be instructed on specific lower extremity stretches to help minimize any residual muscle soreness that you may experience.

The direct benefits are that you will gain a better understanding of your knee function. More specifically, you will be able to compare the difference in strength and jumping ability between your injured and non-injured (or dominant and non-dominant) limb. The indirect benefits are knowing that your participation will help those in the medical field better understand the functional changes that result due to an injury of the anterior cruciate ligament.

The confidentiality measures that will be taken with respect to the collected data include: 1) Locking data in a filing cabinet in which only the investigators have access to and 2) Removing the participant’s name and replacing it with a subject number. The linking information will be kept separately.

Should you have any questions or concerns, please do not hesitate to contact Scott Thomas (the principle researcher), Linda Woodhouse or Siobhan O'Donnell at (416) 967-8717.

I understand that all information and data collected will be kept confidential. I give consent to the investigators to analyze all data collected and potentially publish it, as long as my identity is not revealed.

I realize that my participation in this research is voluntary. If I elect to participate in the study, I have the right, at any time to withdraw from the study without affecting my care at this hospital. I also understand that the investigators may require that I withdraw from the study at any time.

I, ____________________________ have read and fully understand all that is required of me in this research study and knowing all the risks and benefits. I have been given the opportunity to ask questions of the researchers and they answered to my satisfaction.

Participant: ____________________________

print name

signature

date

Witness: ____________________________

print name

signature

date
Appendix 3
Comparison of hop distance scores obtained from the Peak Performance Movement Analysis System versus tape measurement

Prior to participating in this study (between 3 to 26 days), ACLD subjects performed the OLHD as part of another study, whereby the hop distance scores were obtained using a tape measure affix to the ground. This permitted a comparison of the hop distance scores obtained from a direct measurement method to scores obtained using the Peak Performance Motion Measurement System used within this study.

A two-way repeated measures ANOVA demonstrated no significant difference between methods of measurement within limb type (affected and unaffected) and no interaction between method of measurement and limb type. The only significant difference found was between limbs (affected versus unaffected) within each method of measurement (Table 20).

Therefore, hop distance scores obtained from the Peak Performance Motion Measurement System are comparable to those obtained from the more traditional direct measurement method using a measuring tape that is fixed to the ground.
Table 2: Summary of Mean hop distance scores ($\pm$ SEM) by limb type within methods of measurement.

<table>
<thead>
<tr>
<th>Method of Measurement</th>
<th>Unaffected</th>
<th>Affected</th>
<th>Unaffected</th>
<th>Affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance System</td>
<td>0.925</td>
<td>0.96</td>
<td>0.925</td>
<td>0.96</td>
</tr>
<tr>
<td>Test Performance System</td>
<td>0.23</td>
<td>0.27</td>
<td>0.23</td>
<td>0.27</td>
</tr>
<tr>
<td>Analysis System</td>
<td>0.23</td>
<td>0.27</td>
<td>0.23</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Note: The raw data was non-normal therefore, data was transformed (standardized) in order to comply with the assumptions of the analysis of variance. The means ($\pm$ SEM) presented are the transformed data. The $p$-values presented are the transformed (standardized) $p$-values. The $F$-value ($\pm$ SEM) is level of significance for method of measurement and limb type interactions. All $p$-values were determined by two-way repeated measures ANOVA. Hop distance scores were deemed significantly different (denoted by the symbol *) if $p < 0.05$.
Appendix 4
Confidence in Landing Scale

How confident are you in landing a one-leg hop for distance?

Dominant leg: ___________________________ 0% 100%
Non-dominant leg: ________________________ 0% 100%
Appendix 5
QUALITY OF LIFE ASSESSMENT IN ANTERIOR CRUCIATE LIGAMENT DEFICIENCY

SYMPTOMS AND PHYSICAL COMPLAINTS

1. With respect to your overall knee function. How troubled are you by giving away episodes? (Make a slash at the extreme right, i.e., 100, if you are experiencing no giving way episodes in your knee. Please note that this question has two parts. It is concerned with both the severity (1a) and frequency (1b) of the giving way episodes.)

1a 0
Major giving way episodes
Minor giving way episodes

1b 0
Constantly giving way
Never giving way

2. With any kind of prolonged activity (i.e., greater than half an hour) how much pain or discomfort do you get in your knee?

0 100
Severe pain
No pain at all

3. With respect to your overall knee function, how much are you troubled by stiffness or loss of motion in your knee?

0 100
Severely troubled
Not troubled at all

4. Consider the overall function of your knee and how it relates to the strength of your muscles: How weak is your knee?

0 100
Extremely weak
Not weak at all

WORK-RELATED CONCERNS

The following questions are being asked with respect to your job or vocation. The questions are concerned with your ability to function at work and how your knee has affected your current work situation, i.e., your work-related concerns. If you are a full-time student or home maker consider this and any part-time work together. Consider the last three months.

If you are currently not employed for reasons other than your knee then place a check on this line.

5. How much trouble do you have, because of your knee, with turning or pivoting motions at work? (Make a slash at the extreme left, i.e., 0, if you are unable to work because of the knee.)

0 100
Severely troubled
No trouble at all
6. How much trouble do you have, because of your knee, with squatting motions at work? (Make a slash at the extreme left, i.e., 0, if you are unable to work because of the knee.)

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Severely troubled</td>
</tr>
</tbody>
</table>

7. How much of a concern is it for you to miss days from work due to problems or re-injury to your knee? (Make a slash at the extreme left, i.e., 0, if you are unable to work because of the knee.)

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>An extremely significant concern</td>
</tr>
</tbody>
</table>

8. How much of a concern is it for you to lose time from "school" or work because of the treatment of your ACL-deficient knee?

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>An extremely significant concern</td>
</tr>
</tbody>
</table>

RECREATIONAL ACTIVITIES AND SPORT PARTICIPATION OR COMPETITION

The following questions are concerned with your ability to function and participate in these activities as they relate to your ACL-deficient knee. Consider the last three months.

9. How much limitation do you have with sudden twisting and pivoting movements or changes in direction?

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Totally limited</td>
</tr>
</tbody>
</table>

10. How much of a concern is it for you that your sporting or recreational activities may result in the status of your knee worsening?

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>An extremely significant concern</td>
</tr>
</tbody>
</table>

11. How does your current level of athletic or recreational performance compare with your preinjury level?

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Totally limited</td>
</tr>
</tbody>
</table>

12. With respect to the activities or sports that you currently desire to be involved with, how much have your expectations changed because of the status of your knee?

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Expectations totally lowered</td>
</tr>
</tbody>
</table>
13. Do you have to play your recreation or sport under caution? (Make a slash at the extreme left, i.e., 0, if you are unable to play your recreation or sport because of your knee.)

0 Always play under caution
0 Never play under caution

14. How fearful are you of your knee giving way when playing recreation or sport? (Make a slash at the extreme left, i.e., 0, if you are unable to play recreation or sport because of your knee.)

0 Extremely fearful
0 No fear

15. Are you concerned about environmental conditions such as a wet playing field, a hard court, or the type of gym floor when involved in your recreation or sport? (Make a slash at the extreme left, i.e., 0, if you are unable to play recreation or sport because of your knee.)

0 Extremely concerned
0 Not concerned at all

16. Do you find it frustrating to have to consider your knee with respect to your recreation or sport?

0 Extremely frustrated
0 Not frustrated at all

17. How difficult is it for you to “go full out” at your recreation or sport? (Make a slash at the extreme left, i.e., 0, if you are unable to play recreation or sport because of your knee.)

0 Extremely difficult
0 Not difficult at all

18. Are you fearful of playing contact sports? (Circle the “N/A” at the right side of the scale if you do not play contact sport for reasons other than the knee.)

0 Extremely fearful
0 No fear at all

0 100 N/A

The following questions are specially asking about the two most important sports or recreational activities that you do or that you wish to do. Please write them in order.

1. 
2. 

19. How limited are you in playing the number “1” sport or activity? (Make a slash at the extreme left, i.e., 0, if you are unable to play the recreation or sport because of your knee.)

0 Extremely limited
0 Not limited at all

20. How limited are you in playing the number “2” sport or activity? (Make a slash at the extreme left, i.e., 0, if you are unable to play the recreation or sport because of your knee.)

0 Extremely limited
0 Not limited at all
LIFE STYLE

The following questions are concerned with your life style in general and should be considered outside of your work and recreational or sport activities as they relate to your ACL-deficient knee.

21. Do you have to concern yourself with general safety issues (e.g., carrying small children, working in the yard) with respect to your ACL-deficient knee?

| 0 | Extremely concerned | 100 | No concern at all |

22. How much has your ability to exercise and maintain fitness been limited by your knee problem?

| 0 | Totally limited | 100 | Not limited at all |

23. How much has your enjoyment of life been limited by your knee problem?

| 0 | Totally limited | 100 | Not limited at all |

24. How often are you aware of your knee problem?

| 0 | All of the time | 100 | None of the time |

25. Are you concerned about your knee with respect to life style activities that you and your family do together?

| 0 | Extremely concerned | 100 | No concern at all |

26. Have you modified your life style to avoid potentially damaging activities to your knee?

| 0 | Totally modified | 100 | No modifications |

SOCIAL AND EMOTIONAL

The following questions are about your attitudes and feelings as they relate to your ACL-deficient knee.

27. Does it concern you that your competitive needs are no longer being met because of your knee problem? (Make a slash at the extreme right, i.e., 100, if your competitive needs are being met.)

| 0 | Extremely concerned | 100 | Not concerned at all |

28. Have you had difficulty being able to psychologically “come to grips” with your knee problem?

| 0 | Extremely difficult | 100 | Not difficult at all |
29. How often are you apprehensive about your knee?

| 0 | All of the time | 100 | None of the time |

30. How much are you troubled with lack of confidence in your knee?

| 0 | Severely troubled | 100 | No trouble at all |

31. How fearful are you of re-injuring your knee?

| 0 | Extremely fearful | 100 | No fear at all |
Appendix 6
Retrospective Matching of ACLD Subjects and Healthy, Non-injured Controls

In order to evaluate if controlling for differences in inherent athletic ability and leg dominance improves the ability of the OLHD scores to: 1) differentiate ACLD from a healthy, non-injured sample and 2) diagnose ACLD patients from a group of non-injured Controls, subjects were retrospectively matched for two purposes.

Firstly, to correct for differences in inherent athletic ability, subjects were matched according to the hop distance on the unaffected limb of the ACLD to the hop distance (average of the dominant and non-dominant limb) of the Controls (Table 21)

<table>
<thead>
<tr>
<th>ACLD Subject ID No.</th>
<th>ACLD Hop Distance (m) (unaffected limb)</th>
<th>Matched Control Subject ID No.</th>
<th>Controls Hop Distance (m) (average of dominant and non-dominant limbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.88</td>
<td>2</td>
<td>1.93</td>
</tr>
<tr>
<td>2</td>
<td>1.63</td>
<td>9</td>
<td>1.68</td>
</tr>
<tr>
<td>3</td>
<td>1.76</td>
<td>3</td>
<td>1.71</td>
</tr>
<tr>
<td>4</td>
<td>1.44</td>
<td>5</td>
<td>1.48</td>
</tr>
<tr>
<td>5</td>
<td>2.09</td>
<td>10</td>
<td>2.06</td>
</tr>
<tr>
<td>6</td>
<td>1.62</td>
<td>8</td>
<td>1.67</td>
</tr>
<tr>
<td>7</td>
<td>1.79</td>
<td>1</td>
<td>1.92</td>
</tr>
<tr>
<td>8</td>
<td>1.67</td>
<td>6</td>
<td>1.69</td>
</tr>
<tr>
<td>9</td>
<td>1.78</td>
<td>4</td>
<td>1.79</td>
</tr>
<tr>
<td>10</td>
<td>1.57</td>
<td>7</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Table 21 Retrospective matching of ACLD and Controls to correct for differences due to inherent athletic ability. The pairs were matched according to the absolute hop distance on the unaffected limb of the ACLD to the hop distance (average of the dominant and non-dominant limb) of the Controls.
Secondly, in order to control for the impact of leg dominance, subjects were matched according to the absolute distance hopped on the unaffected limb of the ACLD to the hop distance on the limb of corresponding dominance within the Control group (Table 22).

<table>
<thead>
<tr>
<th>ACLD Subject ID No.</th>
<th>ACLD Hop Distance (m) (Unaffected limb)</th>
<th>Matched Control Subject ID No.</th>
<th>Control Hop Distance (m) (Limb of corresponding dominance to the ACLD pair)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.88</td>
<td>2</td>
<td>1.93</td>
</tr>
<tr>
<td>2</td>
<td>1.63</td>
<td>9</td>
<td>1.68</td>
</tr>
<tr>
<td>3</td>
<td>1.76</td>
<td>3</td>
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</tr>
<tr>
<td>4</td>
<td>1.44</td>
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<tr>
<td>5</td>
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<td>1.60</td>
</tr>
<tr>
<td>7</td>
<td>1.79</td>
<td>1</td>
<td>1.93</td>
</tr>
<tr>
<td>8</td>
<td>1.67</td>
<td>6</td>
<td>1.55</td>
</tr>
<tr>
<td>9</td>
<td>1.78</td>
<td>4</td>
<td>1.78</td>
</tr>
<tr>
<td>10</td>
<td>1.57</td>
<td>7</td>
<td>1.67</td>
</tr>
</tbody>
</table>

Table 22 Retrospective matching of ACLD and Controls to correct for differences due to leg dominance. The pairs were matched according to the absolute hop distance on the unaffected limb of the ACLD to the hop distance on the limb of corresponding dominance within the Controls.
The Modified Knee Scoring Scale of Lysholm and Tegner Activity Score Results

With the Modified Knee Scoring Scale of Lysholm scores are classified as either 'excellent' (95-100), 'good' (84-94), 'fair' (65-83), or 'poor' (<64). Significant differences in Lysholm scores were demonstrated between ACLD and Controls (p<0.001). All of the Controls (n=10) scored within the 'excellent' category whereas only 10% of the ACLD subjects (n=1) scored within the same category. The majority (60%) of the ACLD subject's (n=6) scores fell within the 'fair' category (Figure 25).

![Bar graph](image)

**Figure 25** Comparison of overall Modified Knee Scoring Scale of Lysholm scores by group. Ten percent (10%) of the ACLD scores inferred poor knee function (n=1), 60% fair (n=6), 10% good (n=1) and 20% excellent (n=2) whereas 100% of the Controls scores suggested excellent knee function (n=10). There was a significant difference between the ACLD and Control group with respect to overall Lysholm scores (p<0.001).
Upon evaluation of the 8 subcriteria, all ACLD subjects reported varying degrees of instability of the knee (n=10), 80% reported some degree of knee pain (n=8) and other symptoms or problems with function were experienced by ≤ 50% of the ACLD subjects (n≤5).

With respect to the Tegner Activity Score, the Controls demonstrated the greatest range in activity from light labor & swimming to competitive pivot sports (scores 3 to 9). The ACLD pre-injury scores ranged from recreational jumping sports to competitive pivot sports (scores 6 to 9) and their post injury scores from light labor/swimming to recreational pivot sports (3 to 7) (Figure 26).

![Tegner Activity Score Chart]

**Figure 26** Summary of the frequency of Tegner Activity Score Category results for Controls, ACLD pre-injury and ACLD post-injury activity levels. The percentage of subjects who took part in recreational or competitive sports (activity levels ≥ 5) were as follows: ACLD pre-injury 100%, ACLD post-injury 50% and Controls 70%.

The ACLD engaged in more physically challenging activities pre-injury (mean ± standard deviation; 7.7±1.1) compared to Controls (6.4± 2.2; p=0.082) and in less demanding activities
post-injury (4.7±1.3) relative to Controls (6.4± 2.2; p=0.212). However, the only significant difference found was that of the ACLD pre-injury (7.7±1.1) compared to post-injury (4.7±1.3; p=0.004) activities where the ACLD engaged in significantly less demanding activities post injury compared to their pre-injury secondary to their knee condition (Table 24).
### Table 23: Summary of the median (25\(^{th}\) & 75\(^{th}\) percentiles) of the Modified Knee Scoring Scale of Lysholm and Tegner Activity scores by group. Levels of significance (p-values) were determined by the Mann-Whitney Rank Sum test for between group differences and by the Wilcoxon-Signed Rank test for the differences between pre and post activity levels of the ACLD subjects. Tegner scores and were deemed significantly different (identified by the symbol *) if p < 0.05.

- **p value (1)** = level of significance between groups
- **p value (2)** = level of significance within ACLD group
Appendix 8
Controlling for Sources of Variation (Inherent Athletic Ability and Leg Dominance) that may impact the Sensitivity of the Hop Index Scores in the Detection of Lower Limb Functional Limitations

The hop index is influenced by the magnitude of the arithmetic value of the underlying hop distance scores. For instance, two healthy, non-injured individuals of differing athletic abilities, who demonstrate an equal difference in absolute distance hopped between their non-dominant and dominant limbs, will differ in their hop index score. The individual who hopped farther will demonstrate a greater hop index compared to an individual with an inferior hop performance. As a result, their hop indexes are not directly comparable because of the impact of the arithmetic value of the underlying hop distance scores. This source of error may affect the sensitivity of the hop index in the detection of lower limb functional limitations when categorizing a hop index as either normal or abnormal according to the established reference norms.

In order to eliminate the effect that the absolute hop distance (inherent athletic ability) has on the hop index, the ACLD were retrospectively matched to Controls according to distance hopped (Appendix 6-Table 21). And, the ACLD hop index was expressed relative to the hop index of their matched Control (injured/non-injured) / (non-dominant/dominant) (Table 25) to obtain a ratio unconstrained by the effect of the magnitude of the underlying hop distance scores. This ratio allows a comparison of the hop indexes against the defined clinical benchmarks without concern for the effect of the differences in underlying hop distance scores.
The distributions of the re-defined ACLD hop index scores within the normal and abnormal categories were analyzed (Figure 27). Only 33% of the ACLD subjects demonstrated an abnormal hop index (<85%) as defined by Barber et al. (1990) [9] and just 56% had an abnormal hop index (<90%) as defined by Daniel et al. (1982 and 1988) [105, 115].

Distribution of the ACLD Hop Index Scores Expressed Relative to their Matched Control to Correct for the Effect of the Differences in Inherent Athletic Ability

![Figure 27](image-url)

**Table 24** Summary of the hop indexes matched according to hop distance and the ACLD hop index expressed relative to their matched Control (injured/non-injured)/(non-dominant/dominant) to correct for differences in hop index scores attributed to differences in inherent athletic ability.
Differences attributed to leg dominance may also impact the sensitivity of the OLHD scores. In the ACLD population, the hop index is a ratio of the injured to non-injured limb hop distance performance. Consequently, the impact of leg dominance is not corrected for in hop index scores which may result in masking or exaggerating functional limitations in the performance of the OLHD when comparing the ACLD knee to an uninjured knee (for both within and between patient comparisons).

The impact of leg dominance was controlled for (along with differences in inherent athletic ability) through retrospective matching (Appendix 6-Table 22) and the ACLD hop index was expressed relative to their matched Control (injured/non-injured) / (limb ratio of corresponding leg dominance to ACLD pair) (Table 26). This ratio allows a comparison of the hop indexes against the defined clinical benchmarks without concern for the effect of the differences attributed to leg dominance.

<table>
<thead>
<tr>
<th>Matched PAIR (ACLD/Control)</th>
<th>ACJD Injured/Non-Injured</th>
<th>Control</th>
<th>Limb Ratio of Corresponding Leg Dominance to Matched ACLD Pair</th>
<th>Hop IndexACLJD (Relative to Matched Control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 → 2</td>
<td>84</td>
<td>100</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td>2 → 9</td>
<td>88</td>
<td>100</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>3 → 3</td>
<td>86</td>
<td>92</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>4 → 5</td>
<td>94</td>
<td>99</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>5 → 10</td>
<td>83</td>
<td>94</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td>6 → 10</td>
<td>105</td>
<td>108</td>
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<td></td>
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<tr>
<td>7 → 7</td>
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<td></td>
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<tr>
<td>8 → 6</td>
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<td>448</td>
<td>84</td>
<td></td>
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<tr>
<td>9 → 4</td>
<td>88</td>
<td>102</td>
<td>87</td>
<td></td>
</tr>
<tr>
<td>10 → 7</td>
<td>96</td>
<td>97</td>
<td>99</td>
<td></td>
</tr>
</tbody>
</table>

Table 25 Summary of the hop indexes matched according to hop distance and leg dominance and the ACLD hop index expressed relative to their matched Control [(injured/non-injured) / (limb ratio of corresponding leg dominance relative to matched ACLD pair)] to correct for differences in leg dominance.
The distributions of the re-defined ACLD hop indexes within the normal and abnormal categories were analyzed (Figure 28). Only 11% of the ACLD subjects demonstrated an abnormal hop index (<85%) as defined by Barber et al. (1990) [9] and 44% had an abnormal hop index (<90%) as defined by Daniel et al. (1982 and 1988) [105, 115].

Distribution of the ACLD Hop Index Scores Expressed Relative to their Matched Control to Correct for Differences in Inherent Athletic Ability and Leg Dominance

Figure 28 Summary of the distribution of the ACLD hop index scores expressed relative to their matched Control to correct for differences in leg dominance (and inherent athletic ability). Only 11% of the hop index scores (n=1) were abnormal according to reference norms as defined by Barber et al. (1990) [9] whereas 44% (n=4) were abnormal according to references norms defined by Daniel et al. (1982 and 1988) [105, 115].

In summary, controlling for differences in inherent athletic ability and the impact of leg dominance did not improve the diagnostic ability of the hop index in the detection of functional limitations in the given ACLD sample.
Appendix 9
Pearson Product Moment Correlations between OLHD performance (hop distance and hop index) and Measures of Impairment and Perceived Disability by Group

<table>
<thead>
<tr>
<th>Absolute Values</th>
<th>Isokinetic Quadriceps Strength 60° s⁻¹</th>
<th>120° s⁻¹</th>
<th>180° s⁻¹</th>
<th>Single-Leg Vertical Jump</th>
<th>Confidence in Landing</th>
<th>QOL Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACLD limb Hop distance</td>
<td>r = 0.09</td>
<td>p = 0.11</td>
<td>r = 0.33</td>
<td>p = 0.343</td>
<td>r = 0.07</td>
<td>p = 0.857</td>
</tr>
<tr>
<td>Matched Controls Hop distance</td>
<td>r = 0.32</td>
<td>p = 0.396</td>
<td>r = 0.31</td>
<td>p = 0.419</td>
<td>r = 0.30</td>
<td>p = 0.427</td>
</tr>
<tr>
<td>ACLD Hop Index</td>
<td>r = -0.14</td>
<td>p = 0.703</td>
<td>r = -0.16</td>
<td>p = 0.667</td>
<td>r = -0.32</td>
<td>p = 0.361</td>
</tr>
<tr>
<td>Controls Hop Index</td>
<td>r = -0.11</td>
<td>p = 0.772</td>
<td>r = -0.48</td>
<td>p = 0.193</td>
<td>r = -0.45</td>
<td>p = 0.183</td>
</tr>
<tr>
<td>ACLD Hop Index (based on transformed data)</td>
<td>r = -0.17</td>
<td>p = 0.641</td>
<td>r = -0.08</td>
<td>p = 0.825</td>
<td>r = -0.31</td>
<td>p = 0.388</td>
</tr>
</tbody>
</table>

Pearson Product Moment Correlations (r-values) and levels of significance (p-values) for relationships between OLHD performance (hop distance and hop index) and measures of impairment (muscular function and confidence in landing) in addition to perceived disability (QOL score) by group (ACLD limb and matched Controls). All correlations were found to be non-significant except for the moderate to strong association between the hop distance and single-leg vertical jump height in the matched Controls (r=0.68; p=0.0443). All other correlations that demonstrated a moderate (i.e. r> 0.40) correlation appeared skewed when graphed secondary to one or two outliers, level of significance (identified by *) was determined at the p<0.05 level.
March 8, 2001

Mr. Nick Mohtadi
University of Calgary Sport Medicine Centre
2500 University Drive NW
Calgary, Alberta T2N 1N4

Dr.

Dear Mr. Mohtadi,

I am a Master's student in the Department of Rehabilitation Science at the University of Toronto. My thesis is entitled "Determinants of the One-Leg Hop for Distance in the ACL-Deficient Population".

The University requires that written authorization be obtained from yourself to allow the inclusion of the Quality of Life Assessment in Anterior Cruciate Ligament Deficiency Questionnaire in the thesis and to permit the National Library in Ottawa, Canada, to make use of the thesis (i.e. to reproduce, loan, distribute, or sell copies of the thesis by any means and in any form or format).

Attached is a copy of the Quality of Life Assessment in Anterior Cruciate Ligament Deficiency Questionnaire which was retyped for the purpose of administering it to subjects.

If these arrangements meet with your approval, please sign below and return it to me at your earliest convenience. Your assistance in this matter is greatly appreciated.

Sincerely,

Sean O’Donnell, B Sc. (PT), M.Sc.(C)

PERMISSION GRANTED FOR THE USE REQUESTED ABOVE:

[Signature] [Print Name] [Date]