# Endurance of the Hamstring Muscles 9–12 Months After an Anterior Cruciate Ligament Reconstruction with a Hamstring Graft

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# Abstract

## Objective

To assess whether anterior cruciate ligament (ACL) reconstruction with a hamstring graft leads to reduced hamstring endurance 9–12 months post-surgery, to investigate the relationship between hamstring endurance and knee function, and to assess if individuals have reduced hop performance when fatigued.

## Study Design

A cross-sectional inter-limb comparison study was undertaken with participants 9–12 months after an ACL reconstruction with a hamstring graft, and a group of age-, gender- and activity-matched controls.

## Background

In New Zealand, 80% of individuals with an ACL rupture have surgical reconstruction to reduce knee instability. Endurance capability in the muscles controlling the knee is poorly understood in this population despite many sporting activities requiring notable muscle endurance. The hamstring muscles, when active, provide important anatomical support to protect the reconstructed graft. In the absence of good hamstring endurance, fatigue may predispose individuals to re-injury.

## Method

Hamstring endurance was measured using a progressive fatigue test on an isokinetic dynamometer at a joint angular velocity of 120°/second. The dependant variable was the maximum number of repetitions performed. Statistical comparisons were made across injured, uninjured and control group limbs.

Hop performance was measured using a series of hop tests. The single and triple hop for distance were repeated within two minutes of completing the hamstring fatigue protocol. Data analyses involved ANOVA and correlation coefficients.

## Results

There was a significant ($p < 0.05$) deficit in hamstring endurance observed between the injured leg (mean: 111 repetitions, SD 49) and uninjured leg (mean: 136 repetitions, SD 67) of the ACL group, but not between the uninjured and control group legs (mean: 124 repetitions, SD 50).

There were no significant ($p<0.05$) correlations found between the perceived or performance-based knee function and hamstring endurance of the ACL-injured leg ($R = -0.23$ to $0.21$).

The single and triple hop distance of the injured leg was significantly less ($p < 0.05$) than the uninjured leg, pre and post hamstring fatigue (effect size 0.49 and 0.35 respectively). For both hops, there was a significant difference across pre- and post-fatigue measures irrespective of legs (effect size 0.53 and 0.76 respectively). There was no significant difference between the uninjured and control legs for the single hop for distance (effect size 0.01). A significant interaction effect ($p = 0.049$) indicated a different response to fatigue across the uninjured and control legs for the triple hop for distance; however, there was a low effect size (0.08).

## Conclusion

The observed 18% deficit in hamstring endurance across the ACL-reconstructed individual's limbs is indicative of a notable loss in performance of the hamstring muscles at 9–12 months post-surgery, and provides initial support for the inclusion of hamstring endurance training in rehabilitation programmes post-surgery.

When the hamstring muscles are fatigued, single and triple hop distances are significantly less on the ACL-injured leg compared to the uninjured leg. Considering a large proportion of injuries occur in the final stages of a sporting event, hop testing under fatigued conditions is worthy of attention for return-to-sport testing.

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# Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signed:

Date: 12$^{th}$ December 2020

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# Chapter 1 Introduction

## 1.1 Statement of the Problem

Anterior cruciate ligament (ACL) rupture is a common injury in New Zealand, occurring most frequently in children and young adults during sport and recreational activities (M. Anderson, Browning, Urband, Kluczynski, & Bisson, 2016; Gianotti, Marshall, Hume, & Bunt, 2009; Sutherland, Clatworthy, Fulcher, Chang, & Young, 2019). The ACL is paramount for maintaining knee joint stability (M. Anderson et al., 2016). Without the ACL, the anterior and rotatory stability of the knee is often compromised. This in turn can result in episodes of the knee giving way that may lead to further damage within the knee joint, particularly to the menisci, and ultimately the sequalae of osteoarthritis can become apparent at a young age (Hohmann, Bryant, & Tetsworth, 2016; Hohmann, Tetsworth, & Glatt, 2018). Ajuied and colleagues (2014) showed that the relative risk (RR) of developing even minimal osteoarthritis after ACL injury, regardless of whether management is surgical or non-surgical, is 3.89 ($p < 0.0001$), and the relative risk of developing moderate to severe osteoarthritis after ACL injury is 3.84 ($p < 0.0004$). In addition, up to 50% of individuals who have had an ACL reconstruction will have radiographic evidence of osteoarthritis within 10–15 years of surgery (Ajuied et al., 2014; Lohmander, Englund, Dahl, & Roos, 2007). Furthermore, it has been shown (Khan et al., 2019) that there is a seven-fold increase in the odds of having a total-knee joint arthroplasty (OR 6.96, 95% CI 4.73 to 10.31) from osteoarthritis secondary to ACL injury. As a result of these events, a significant health and financial burden is placed upon both the individual and the healthcare system with every ACL injury, regardless of whether or not an individual opts for conservative or surgical management (Filbay, Culvenor, Ackerman, Russell, & Crossley, 2015; Gianotti et al., 2009; Suter et al., 2017).

Surgical reconstruction is considered by many to be the gold standard for treatment (Abrams et al., 2014). Internationally, up to 75% of individuals who sustain an ACL injury will go forward for surgery (Collins, Katz, Donnell-Fink, Martin, & Losina, 2013; Nordenvall et al., 2012; Sanders et al., 2016). It has recently been shown (Sutherland et al., 2019), that the overall annual incidence of ACL reconstruction in NZ has increased by 58% from the last report for the years 2000–2005, to the current report for the years 2009–2016. In New Zealand, between 2009 and 2016, a total of 20,751 primary ACL reconstruction surgeries were funded by Accident Compensation Corporation (ACC), the main funding body for such surgery (Sutherland et al., 2019). The mean total cost of each injury is estimated to be $11,157 per person, with a total cost to the New Zealand health system of $65,644,788 over 5 years (Gianotti et al., 2009).

An ACL injury involves a lengthy period of time away from sport and a long rehabilitation pathway post-surgery. The return to sport is reported to be from 6 to 12 months post-surgery for the majority of people (Ardern, Webster, Taylor, & Feller, 2010b). Despite apparent success with both rehabilitation and a return to sport, the rate of re-injury or rupture of the graft has been reported at 6-27% (Grindem et al., 2015; Kyritsis, Bahr, Landreau, Miladi, & Witvrouw, 2016). A key factor in the successful rehabilitation of the knee following ACL reconstruction is the restoration of quadriceps and hamstrings muscle performance (Palmieri-Smith & Lepley, 2015; Undheim et al., 2015). The focus of the current research is on hamstring muscle function. These muscles, when activated, have considerable potential to reduce anterior tibial translation (ATT), and therefore improve knee stability (Catalfamo, Aguiar, Curi, & Braidot, 2010; More et al., 1993; Yanagawa, Shelburne, Serpas, & Pandy, 2002). To date, research has identified that, after ACL reconstruction, the hamstring muscles have notable strength deficits which can reach levels as high as 34% (Hohmann et al., 2016; Hsiao, Chou, Hsu, & Lue, 2014). Such deficits in strength are not surprising, particularly in respect of the semitendinosus muscle, the tendon of which is often utilised as the graft of choice for the ruptured ACL (Konishi & Fukubayashi, 2010; D. Lee, Shim, Yang, Cho, & Kim, 2019). As such, the muscle's ability to return to pre-operative levels of performance is compromised.

While strength is an important aspect of function, it can be argued that the endurance capability of the hamstring muscles is worthy of consideration. In many sports, repeated knee joint activity requires a sustained ability to activate the hamstrings to appropriate levels to maintain stability at the joint, the rationale being that activation of these muscles provides increased stiffness that resists anteriorly directed loading on the ACL graft (Blackburn, Norcross, & Padua, 2011; McNair, Wood, & Marshall, 1992) during sporting activities which involve hopping, side stepping, jumping and landing. Surprisingly, compared to the research on the strength of hamstring muscles after an ACL reconstruction, there are only a small number of researchers that have investigated the role of muscle endurance in the recovery of knee function after an ACL reconstruction. Deficits of up to 22% in hamstring endurance have been demonstrated up to 2 years after an ACL reconstruction (D. Lee, Lee, Jeong, & Lee, 2015; Tow, Chang, Mitra, & Tay, 2005; Vairo, 2014); however, the results are conflicting as there is one study which did not find any significant difference in hamstring endurance at 21 months post-surgery (Vairo et al., 2008). The aforementioned studies have all investigated hamstring endurance using repeated maximal effort testing, and while this is an important component of hamstring muscle function, another approach is to examine submaximal activity by fatiguing the hamstring muscles utilising different energy systems to those required during maximal activations. A prolonged endurance test that starts at submaximal effort levels would test the aerobic capacity of the muscle compared to that of a repeated maximal effort test that requires primarily anaerobic activity. It is the former scenario that is more prevalent during sports and recreational activities. There are no studies to date which have included a submaximal element in their hamstring endurance test after ACL reconstruction.

A secondary aim of the current study is concerned with the return to sport. There is ongoing debate in the literature regarding return-to-sport decision making and, to date, a validated and internationally accepted return-to-sport test battery remains elusive. However, hop performance is widely accepted as an important factor in this decision-making process (Gustavsson et al., 2006; Kyritsis et al., 2016). Achieving a Limb Symmetry Index (LSI) (involved/uninvolved X 100) of greater than 90% on these hop tests is regarded as a requirement prior to the return to sport (Thomeé et al., 2011). At 11 months after ACL reconstruction, 68% of a group of individuals who all had an LSI of greater than 90% under non-fatigued conditions for the single hop for distance demonstrated an abnormal LSI when assessed under quadriceps fatigue (Augustsson, Thomeé, & Karlsson, 2004). Injuries are most common towards the end stages of a sporting event, when individuals are fatigued (Dugan & Frontera, 2000; Ostenberg & Roos, 2000); therefore, it has been suggested that undertaking these hop tests in a fatigued state would provide a more comprehensive assessment of lower limb function following an ACL reconstruction (Augustsson et al., 2004; Augustsson et al., 2006). To date there are no studies which have investigated hop test results when the hamstrings are in a fatigued state in individuals after an ACL reconstruction.

## 1.2 Purpose of the Study

The purpose of the study was threefold:

1. To measure the submaximal hamstring endurance on the injured leg of individuals who have undergone an ACL reconstruction using a hamstring graft 9–12 months previously, and compare this to both their uninjured leg and also the leg of an age-, gender- and activity-matched control.
2. To investigate if there is a relationship between hamstring endurance and knee function (both self-reported and performance-based) of the injured leg 9–12 months after ACL reconstruction with a hamstring graft.

3. To measure hop test performance of the injured leg 9–12 months after ACL reconstruction with a hamstring graft when under fatigued conditions, and compare this to the uninjured leg and the leg of an age-, gender- and activity-matched healthy control.

## 1.3 Significance of the Problem

The results of this study may have significance for health professionals who are involved in the post-surgical rehabilitation of individuals following ACL reconstruction. They may encourage health professionals to consider the role of hamstring muscle endurance re-training as an integral component of the rehabilitation programme for those who have had an ACL reconstruction with a hamstring graft. It may also provide information with regard to the impact of hamstring muscle fatigue on functional performance. Additionally, if significant differences are found in hop performance under fatigued conditions, then it may highlight the need for health professionals to consider testing individuals under fatigued conditions during the return-to-sport assessment following an ACL reconstruction.

# Chapter 2 Review of Literature

## 2.1 Introduction

This chapter begins with an explanation of the search strategy used for the literature review. This is followed by an outline of hamstring function and its role in the ACL-deficient knee. A review of hamstring morphology after ACL reconstruction ensues, with the peripheral and central process of muscle fatigue outlined thereafter. A review of hamstring endurance after ACL reconstruction with a hamstring graft is then explored, followed by a review of muscle strength after ACL reconstruction. The relationship between strength and self-reported function is also discussed here. Hop performance after ACL reconstruction is then discussed, followed with a review of hop performance under fatigue. Again, the relationship between hop performance and self-reported function is also discussed here. Finally, a review of return-to-sport decision making concludes the chapter.

## 2.2 Search Strategy

An initial search of the literature was performed from which an extensive list of keywords was obtained. This list included terms specific to ACL injury of the knee, ACL reconstruction of the knee and hamstring function. These words were: knee, ACL, reconstruction, surgery, strength, endurance, neuromuscular, function, return to sport, hop test(ing), limb symmetry index, semitendinosus, gracilis, bone-patellar-tendon-bone, fatigue, isokinetic, isometric, dynamometer, hamstring, quadriceps. Six electronic databases were searched using these keywords, including AMED, PEDro, Sports Direct, MEDLINE, CINAHL and Sports Discus. The literature review was enhanced by examining the reference lists of included articles and previous review papers on ACL reconstruction, and by utilising Scopus to locate articles which had cited particular authors/research studies.

## 2.3 Hamstring Function & Role in the ACL-Deficient Knee

The ACL is the primary structure in the knee which provides passive restraint to ATT and internal rotation of the tibia on the femur (Butler, Noyes, & Grood, 1980; Sakane et al., 1999). Without the ACL, laxity is increased and the anterior stability of the knee can be compromised which in turn can result in poor knee function (Hohmann et al., 2016; Hohmann et al., 2018).

The hamstring muscles are reported to act as an additional restraint to ATT alongside the ACL. There has been a number of cadaveric and model-based studies which have demonstrated that the hamstring muscles can reduce ATT in both an ACL-deficient knee and a knee with an intact ACL (Catalfamo et al., 2010; G. Li et al., 1999; MacWilliams, Wilson, DesJardins, Romero, & Chao, 1999; More et al., 1993; Yanagawa et al., 2002). The change in ATT with knee movement is greater in an ACL-deficient knee (More et al., 1993; Yanagawa et al., 2002). More and colleagues (1993) performed a cadaveric study investigating the kinematics of the knee during a squatting task with both a healthy knee and an ACL-deficient knee. The addition of 90N of hamstring load resulted in a significant decrease in ATT, which was more pronounced in the ACL-deficient group. In addition, they showed that 90N of hamstring load significantly reduced tibial internal rotation during the flexion phase of a squatting task. This reduction was more pronounced during higher angles of knee flexion, which likely reflects the greater lever arm over which the hamstring force would be acting (More et al., 1993). These findings have been supported in another cadaveric study investigating knee kinematics during a similar task (MacWilliams et al., 1999). One research group (Yanagawa et al., 2002) used bioengineering models to calculate ATT at various activation levels. The findings of this model-based study indicated that peak ATT occurs at 10° of knee flexion, and is inversely related to hamstring co-contraction. In the same study, it was shown that ATT decreased by 5mm with a 100% maximum hamstring contraction in the intact knee. In the ACL-deficient knee, ATT decreased by 12mm with a 100% maximum hamstring contraction (Yanagawa et al., 2002). These findings support the view that the hamstring muscles play an important role in healthy, ACL-deficient and ACL-reconstructed knees reducing ATT and, hence, potentially improving knee stability.

Despite the effect of the hamstring muscles on improving knee joint stability, increased hamstring muscle force during functional activity may have less favourable consequences on the loading of the articular cartilage. Catalfamo and colleagues (2010) investigated the impact of increased hamstring activation on the knee joint in an ACL-deficient knee. They demonstrated that the peak hamstring force required to compensate for ATT during gait led to a 115% increase in tibiofemoral joint loading during gait. Such findings would be particularly important where meniscal damage/resection had occurred, increasing the potential for OA in later years.

Hamstring muscle stiffness may also play an important role in improving knee joint stability in an ACL-deficient knee. Muscle stiffness is defined as the ratio of the change in muscle force to the change in muscle length (McNair et al., 1992). When an active muscle is lengthened by a transient stretch, there is a resultant resistance to that stretch by the muscle fibres and tendon by increasing their force output. During a giving-way episode in an ACL-deficient knee, the anterior translation of the tibia on the femur is likely to place a stretch on the hamstring muscles and secondary ligamentous and capsular restraints. Therefore, an increase in hamstring stiffness in an ACL-deficient knee may reduce the amount of ATT and prevent a giving-way episode by increasing knee joint stability. It has been shown (McNair et al., 1992), that hamstring muscle stiffness is positively correlated with functional ability at three levels of hamstring muscle activation, namely 30%, 45% and 60% of maximum voluntary effort in an ACL-deficient knee. Later work by Jennings and Seedhom (1998) demonstrated a significant difference in hamstring muscle stiffness between ACL-deficient knees and both the uninjured leg and a healthy control group. They have also shown a significant difference between hamstring muscle stiffness at 30% and 45% of maximum voluntary effort, with greater levels of stiffness at higher levels of muscle contraction. More recently, Blackburn and colleagues (2011) demonstrated a significant and negative correlation between ATT and hamstring stiffness in a healthy population. They did not find any significant correlation between ATT and hamstring strength, or hamstring strength and hamstring stiffness. They concluded that hamstring stiffness was more important than hamstring strength with regard to improving knee joint stability and that stiffer hamstrings would allow a smaller change in hamstring length, which in turn would result in lower levels of ATT and ACL loading.

McNair and Marshall (1994) demonstrated a significant relationship between lateral hamstring activity and the peak vertical ground reaction force (GRF) during a landing task in ACL-deficient subjects. Participants with lower ground reaction forces had higher levels of hamstring muscle activity, and there was also a moderate correlation between lower GRF and ATT, with subjects with lower GRF having less ATT. This would suggest that increased hamstring muscle activity helps to stabilise the knee joint during landing tasks. It has also been shown (Steele & Brown, 1999), that some ACL-deficient individuals have a delay in hamstring activity compared to a control group to ensure peak hamstring activity was more synchronous with the timing of initial foot contact, where tibiofemoral shear force is high.

In summary, greater inherent hamstring muscle stiffness and activation can contribute to reducing ATT when the ACL is deficient. Similarly, it also has the potential to protect the hamstring graft post-surgery. Hence, the hamstring muscles play an important role in improving knee joint stability and function.

## 2.4 Hamstring Morphology after ACL Reconstruction

Grafting of the hamstring muscles, predominantly the semitendinosus, is a popular choice for ACL reconstruction and is well documented in the literature (Konishi & Fukubayashi, 2010; D. Lee et al., 2019; Papandrea, Vulpiani, Ferretti, & Conteduca, 2000; Suijkerbuijk et al., 2018). Where possible, the semitendinosus tendon alone will be harvested; however, if this is not of sufficient length or size, the gracilis tendon will also be harvested (Nakamura et al., 2002). A number of researchers have investigated the short- and long-term effects of hamstring tendon harvest on the morphology and structural characteristics of this muscle group as a whole. The hamstring and gracilis tendons have been shown to regenerate in the majority but not all cases. Semitendinosus and gracilis regeneration has been reported in 67–87% and 77%–81% of cases respectively up to 27 months after an ACL reconstruction (Eriksson et al., 2001; D. Lee et al., 2019; Nomura, Kuramochi, & Fukubayashi, 2015; Suijkerbuijk et al., 2018). In up to 25% of cases (Nomura et al., 2015), there has been no tendon regeneration observed. The reasons underlying a lack of tendon regeneration remains unclear (Suijkerbuijk et al., 2018).

Hamstring tendon regeneration commences one to two months following an ACL reconstruction and continues to progress through different stages until 18 months post-surgery. This has been investigated using both ultrasound (US) and magnetic resonance imaging (MRI). Within the first 6 months post-surgery, tendon regeneration begins in an anatomical position and the tissue is irregular, hypoechoic and has a larger cross sectional area than pre-operatively (D. Lee et al., 2019; Papandrea et al., 2000; Rispoli, Sanders, Miller, & Morrison, 2001). By 9–12 months, the tendon edges would be expected to appear more distinct and the tendon structure to appear more uniform. In a study by Rispoli and colleagues (2001), when the tendon structure was analysed between 7 and 12 months post-surgery, 33% of individuals had normal tendon morphology up to the distal 3–4cm, with the distal tendon still ill-defined. Papandrea and colleagues (2000) reported persistent irregularities at 12 months post-surgery although, overall, the tendon structure was more uniform. By 18 months post-surgery, the entire semitendinosus tendon has been shown to have returned to normal tendon structure (Papandrea et al., 2000). With persistent irregularities in tendon structure up to 18 months post-surgery, one might assume that these changes would continue to have a negative impact on hamstring muscle performance at 9–12 months post-surgery.

Changes have also been noted with regard to semitendinosus and gracilis muscle length, volume, and cross-sectional area (CSA). A number of authors (Eriksson et al., 2001; Konishi & Fukubayashi, 2010; Nomura et al., 2015; Williams, Snyder-Mackler, Barrance, Axe, & Buchanan, 2004) have shown that the volume, length and CSA of the hamstring muscle (contractile elements) in the ACL-reconstructed limb were significantly less than that in the uninvolved limb up to 28 months post-surgery. These reductions in hamstring muscle volume and length following ACL reconstruction may influence hamstring strength in the involved leg. A significant and positive relationship has been demonstrated between hamstring strength and hamstring muscle volume (r = 0.427–0.611) and length (r = 0.458) (Nomura et al., 2015) in the ACL-reconstructed leg. One could therefore assume that with a reduction in these three factors, there would also be a reduction in hamstring muscle strength.

As outlined above, there are extensive changes to the semitendinosus and gracilis muscle-tendon complexes which persist for up to 2 years after an ACL reconstruction. Ultimately, these changes in tendon morphology as well as the reductions in hamstring muscle volume, length and CSA are likely to have a combined impact on hamstring muscle strength. With reduced strength, the ability of the hamstring muscles to reduce ATT and improve knee joint stability is limited.

## 2.5 Muscle Fatigue

The primary focus in the current study is on muscle fatigue and its effects on functional performance. However, to appreciate its effect upon function in ACL-reconstructed individuals, a review of literature pertaining to muscle fatigue in general is presented. Thereafter, the research associated with hamstring muscle fatigue, and the effect of fatigue in an ACL-reconstructed population is presented. The central tenet is that hamstring fatigue may lead to reduced performance in both maximal effort and endurance-based performance tests such as the hop for distance tests. Such changes may serve as a clinical marker for increased loading on the ACL graft.

Muscle fatigue is defined as a reduction in the maximal force or power-producing capacity of a muscle regardless of whether or not the activity can be sustained (Enoka & Duchateau, 2008; Gandevia, Allen, Butler, & Taylor, 1996). There are multiple mechanisms involved in the development of muscle fatigue encompassing both peripheral and central processes (Allen, Lamb, & Westerblad, 2008; Cairns, 2013; Hargreaves et al., 1998; Hunter, 2014; Kirk, Trajano, Pulverenti, Rowe, & Blazevich, 2019; Taylor & Gandevia, 2008). Changes in the performance of any site along the pathway from the motor cortex to the muscle fibre may influence the extent of muscle fatigue. The development of muscle fatigue depends on a number of factors which include: the type of task involved, e.g., force task versus position task, and high intensity/short duration versus low intensity/prolonged duration (Enoka & Duchateau, 2008; Hunter, Duchateau, & Enoka, 2004; K. Thomas, Elmeua, Howatson, & Goodall, 2016); the type of muscle contraction involved, e.g., isometric versus concentric (Cairns, Knicker, Thompson, & Sjogaard, 2005; Gruet et al., 2014); the muscle group under investigation, e.g., quadriceps, elbow flexors, ankle dorsiflexors (Enoka & Duchateau, 2008); the intensity of the contraction, e.g., maximal or submaximal (Gruet et al., 2014; Taylor & Gandevia, 2008); and age and gender (Enoka, 2012; Enoka & Duchateau, 2008). Given the number of different factors which can influence muscle fatigue, investigating the causes of muscle fatigue is beyond the scope of the current project; however, a succinct review is provided. There are two main concepts presented in the literature, peripheral fatigue which results from impairments within the working muscle itself and central fatigue, also labelled central activation failure, which results from reduced motor drive from the central nervous system (Allen et al., 2008; Cairns et al., 2017; Debold, 2016). The main focus of the current study is the development of hamstring fatigue during a submaximal effort task in an ACL-reconstructed population. Previous research in this population has investigated hamstring fatigue during a maximal effort task only. Peripheral and central fatigue processes are involved in both maximal effort and submaximal effort exercise (Kent Braun, 1999; Taylor & Gandevia, 2008); however, it has long been known that the etiology of fatigue depends on the level of exercise intensity (Fitts, 1994).

Peripheral fatigue involves processes that occur at or distal to the neuromuscular junction including inhibition of the contractile properties of the muscle via metabolic changes in the muscle, depletion of muscle glycogen and excitation-contraction coupling failure (Debold, 2016; Fitts, 1994; Kent Braun, 1999; Taylor & Gandevia, 2008). Fatigue is also influenced by muscle fibre type, with greater fatigue resistance in those muscles with a larger proportion of type I muscle fibres (Allen et al., 2008; J. Li et al., 2002). During maximal effort exercise, anaerobic metabolic processes are predominant and result in an increase in intracellular metabolites such as hydrogen and phosphate which are known to reduce peak muscle force (Cairns et al., 2017). In contrast, submaximal effort exercise utilises aerobic metabolic processes more. Muscle cell metabolites such as hydrogen, lactate and phosphate remain largely unchanged during submaximal exercise, and fatigue is thought to be influenced to a greater degree by muscle glycogen depletion, particularly during exercise at moderate intensity levels, e.g., greater than 60% of $VO_2$max (Bergstrom, Hermansen, Hultman, & Saltin, 1967; Hermansen, 1971). At low intensity exercise, free fatty acids provide the primary source of energy (Saltin & Karlsson, 1971). However, there is an overlap across these processes depending on the level of effort during the submaximal task.

Bergstrom et al. (1967) and Hermansen, Hultman, and Saltin (1967) were among the first authors to describe a direct relationship between the concentration of glycogen in the muscle and the time to fatigue during exercise at 60%–80% of maximal oxygen uptake. It is now well established that a depletion in glycogen stores is associated with muscle fatigue during moderately intense submaximal exercise (Allen et al., 2008; Bergstrom et al., 1967; Fitts, 1994; Hermansen et al., 1967). The exact mechanisms underpinning the reduction in force during fatigue due to glycogen depletion are not fully understood (Allen et al., 2008). However, it is thought that glycogen depletion during long, exhausting exercise may cause muscle fatigue due to an associated reduction in the rate of sarcoplasmic reticulum calcium release (Chin & Allen, 1997; Helander, Westerblad, & Katz, 2002; Ortenblad, Nielsen, Saltin, & Holmberg, 2011; Stephenson, Nguyen, & Stephenson, 1999).

As mentioned above, a change in the level of metabolites in the muscle will result in inhibition of the contractile properties of the muscle, and will lead to muscle fatigue. It has long been understood that the production of lactate during muscle activity is related to muscle fatigue. The production of lactate is associated with glycogen depletion, and is produced notably at work loads of greater than 60% of maximum aerobic capacity (Fitts, 1994). With an increase in lactate accumulation, and a reduction in muscle pH, increased amounts of hydrogen ions accumulate with accompanying changes in potassium, sodium, calcium, and magnesium. Ultimately, as the task/exercise proceeds, a reduction in muscle force-generating capacity is observed due to these metabolic changes and their subsequent interference with important steps in cross-bridge formation (Allen et al., 2008; Debold, 2016; Fitts, 1994; Nelson & Fitts, 2014). These metabolic changes have a greater influence during maximal effort exercise (Fitts, 1994).

During exercise where energy demand is high, creatine phosphate breaks down to creatine and phosphate. Creatine has a minimal effect on muscle contractile processes; however, an increase in myoplasmic phosphate can inhibit muscle force production due to its direct effect on cross-bridge function, which results in a decrease in force production (Allen et al., 2008; Bruton & Wretman, 1997; Nelson & Fitts, 2014; Phillips, Wiseman, Woledge, & Kushmerick, 1993). This increase in phosphate can also cause a reduction in myofibrillar calcium sensitivity, and this may have a significant effect on force production in the later stages of fatigue when there is a decrease in tetanic calcium (Debold, 2016; Fitts, 1994). These findings have been confirmed by Cairns and colleagues (2017). These researchers demonstrated that changes in muscle metabolites, which included a reduction in muscle adenosine triphosphate and phosphocreatine and an increase in muscle lactate, were linearly correlated with the decline of peak maximal voluntary activation force for the quadriceps muscle during intermittent maximum voluntary contractions (MVC). The fatigue protocol consisted of 18 MVCs for seven seconds duration, followed by three seconds of rest, and repeated over three minutes.

Excitation-contraction coupling failure can occur due to impaired calcium handling at the sarcoplasmic reticulum (Allen et al., 2008; Debold, 2016). This has been reported for the quadriceps muscle after a variety of exercise types, both maximal and submaximal, including isokinetic knee extension (C. Hill, Thompson, Ruell, Thom, & White, 2001; J. Li et al., 2002), sprint cycling (Hargreaves et al., 1998) and prolonged cycling/cross-country skiing (Duhamel, Perco, & Green, 2006; Gejl et al., 2014). It has not been investigated for the hamstring muscle group specifically to date. This deterioration in calcium handling was initially thought to be attributed to the fibre type composition of the particular muscles involved in the task at hand. Li and colleagues (2002) showed that the impairment in calcium handling with quadriceps muscle fatigue was related to a larger proportion of fast twitch muscle fibres in the muscle. In contrast, Cairns and colleagues (2017) did not observe any correlation between calcium handling deterioration and muscle fibre type for either the quadriceps or abductor pollicis longus muscles. The muscle fatigue protocol utilised in each study differed considerably, and may explain the conflicting results, with the former study inducing fatigue with 50 repetitions of maximal effort concentric knee extension on the isokinetic dynamometer, in contrast to 18 intermittent isometric contractions, measured using a force transducer, over three minutes for the latter.

Central fatigue refers to fatigue processes which occur more proximally, namely at or proximal to the site of motor axon stimulation, and has been defined as a progressive failure of voluntary activation of the muscle, which has been induced by exercise (Carroll, Taylor, & Gandevia, 2017; Gandevia, 2001). Central fatigue has been shown to contribute to muscle fatigue in a range of muscle groups including the quadriceps (Cairns et al., 2017; Finn, Taylor, Rouffet, Kennedy, & Green, 2018; Goodall, Howatson, & Thomas, 2018), dorsiflexors (Kent Braun, 1999), biceps brachii (McNeil, Giesebrecht, Gandevia, & Taylor, 2011; Schillings, Hoefsloot, Stegeman, & Zwarts, 2003), triceps brachii (Martin, 2006), and hamstring muscles (Marshall, Lovell, Jeppesen, Andersen, & Siegler, 2014). Central fatigue processes are apparent during both maximal and submaximal exercise (Bigland-Ritchie, Johansson, Lippold, & Woods, 1983; Cairns et al., 2017; Gandevia et al., 1996; Goodall et al., 2018; Maluf & Enoka, 2005), with many of the same mechanisms evident. However, it is now thought that central fatigue plays a greater role in submaximal fatigue when compared to maximal effort exercise, where peripheral mechanisms are more dominant (Hunter, Butler, Todd, Gandevia, & Taylor, 2006; Søgaard, Gandevia, Todd, Petersen, & Taylor, 2006). Central fatigue can best be measured accurately during maximal muscle contractions (Søgaard et al., 2006; Taylor & Gandevia, 2008), which makes investigation of central fatigue more difficult for submaximal work.

One method to assess whether or not central fatigue is present is to analyse the voluntary activation of the muscle combined with electrical stimulation to the motor nerve (Dekerle, Greenhouse-Tucknott, Wrightson, Schäfer, & Ansdell, 2019; Taylor & Gandevia, 2008). Any motor units not recruited voluntarily or not firing at optimal levels will produce a larger transient force when stimulated (Herbert & Gandevia, 1999; Kennedy, McNeil, Gandevia, & Taylor, 2014). The greater the force produced with stimulation, the greater the failure of voluntary activation (Gandevia et al., 1996). Voluntary activation can fail at any point along the pathway from the spinal cord to the motor cortex in the brain, including at supraspinal centres (Taylor & Gandevia, 2008). Supraspinal fatigue can be assessed using transcranial magnetic stimulation of the motor cortex (Dekerle, Ansdell, Schäfer, Greenhouse-Tucknott, & Wrightson, 2019; Gandevia et al., 1996; Todd, Taylor, & Gandevia, 2003). Elicitation of superimposed twitches from the muscle being assessed, during maximal muscle activation provides some evidence that, at the time of stimulation, motor cortical output was not maximal and therefore not sufficient to activate all available motor units (Gandevia et al., 1996; Sidhu, Bentley, & Carroll, 2009), ultimately leading to reduced muscle force production (Taylor & Gandevia, 2008).

A reduction in motor unit firing rates is thought to be an element of central fatigue (Bigland-Ritchie, Johansson, Lippold, Smith, & Woods, 1983; Bigland-Ritchie, Thomas, Rice, Howarth, & Woods, 1992). It is thought to occur due to a decrease in excitatory input to the motor unit, an increase in inhibitory input to the motor unit and/or a decrease in the responsiveness of the motor neurons through a change in their intrinsic properties (Finn et al., 2018; Goodall et al., 2018; Gruet et al., 2014; Taylor & Gandevia, 2008). Motoneuron excitability from descending drive has been shown to be reduced in both the elbow flexors (McNeil et al., 2011) and quadriceps muscles (Finn et al., 2018) during sustained submaximal exercise, due to intrinsic changes to the motoneuron itself. Additionally, descending drive becomes less than optimal for force production during sustained and repeated fatiguing contractions (Gandevia et al., 1996; Hunter et al., 2006). This may not be due to a reduction in the absolute level of descending drive, but more its ability to drive the motoneurons (Finn et al., 2018).

Another mechanism of central fatigue involves neural feedback to the central nervous system from the muscle via group III and IV afferents which are metabolically sensitive (Amann, Proctor, Sebranek, Pegelow, & Dempsey, 2009; Kennedy et al., 2014; Taylor & Gandevia, 2008). Lactate, hydrogen (H+) or potassium (K+) can be released into the interstitium from activated muscle fibres and create a feedback loop whereby group III and IV afferents are stimulated. In the presence of fatiguing exercise, group III and IV afferent firing rates have been shown to be elevated (Kaufman & Rybicki, 1987; Pollak et al., 2014) and can inhibit some or all of the above-mentioned central processes of muscle activation (Cairns et al., 2017). Reduced motoneuron output due to stimulation of group III and IV afferents may result from a direct inhibition of the motoneuron for some muscle groups, a reduction in descending drive from the motor cortex, or a reduction in excitatory input through presynaptic inhibition of group Ia afferents (Taylor, Amann, Duchateau, Meeusen, & Rice, 2016). These processes result in reduced voluntary activation. This has been demonstrated for the elbow flexors and adductor pollicis during a maximal isometric exercise (Gandevia et al., 1996; Kennedy et al., 2014). More general exercise has also been shown (Amann et al., 2011; Amann et al., 2009) to cause inhibitory influence on the output from the motoneuron pool due to group III and IV afferents, namely during high intensity cycling. It has been shown (Kennedy et al., 2014; Sidhu et al., 2014) that this inhibitory influence not only affects the muscles directly involved in the fatiguing exercise or task; there is also some crossover to muscle/muscle groups not directly involved in the locomotive task.

Central fatigue also appears to be more prevalent in fast twitch muscle fibres (Allen et al., 2008; Cairns & Lindinger, 2008). Although historically the hamstring muscles were thought to have a higher percentage of fast twitch muscle fibres (Garrett, Califf, & Bassett, 1984), a recent study by Evangelidis and colleagues (2017) showed a uniform distribution of slow and fast twitch fibres in a group of young healthy active participants. It seems likely that the hamstring muscles are subject to a combination of both peripheral and central fatigue processes during an intermittent submaximal fatiguing task.

The impact of sporting exercise on the reduction in hamstring strength is well documented (Coratella, Bellini, & Schena, 2016; Coratella, Grosprêtre, Gimenez, & Mourot, 2018; Marshall et al., 2014; Page, Marrin, Brogden, & Greig, 2019; Sarre, Lepers, & van Hoecke, 2005; Wollin, Thorborg, & Pizzari, 2017) and the deficit has been reported to be as high as 17% immediately after sporting activity when compared to pre-sport measures (Wollin et al., 2017). However, fatigue processes have not been widely studied in the hamstring muscles, with more research for the quadriceps, elbow flexors, ankle dorsiflexors and abductor pollicis. Marshall and colleagues (2014) investigated hamstring muscle fatigue in a group of soccer players during a simulated soccer match. They found that there was a significant reduction in maximal voluntary torque at the end of each 45-minute half which was attributable to central motor output reductions to the biceps femoris as measured by electromyography. There were no changes noted in the size and shape of the resting twitch, and therefore these authors concluded that there was no peripheral muscle fatigue of the hamstrings evident. They also found a reduction in the rate of force development of the hamstring muscles after 15 minutes of play, again due to a reduction in central motor output. Coratella and colleagues (2018) showed some similar but also some conflicting results. In agreement with the study by Marshall and colleagues (2014), they have shown a significant reduction in hamstring MVC after a submaximal isometric fatiguing protocol at 70% MVC. They have also demonstrated evidence of central fatigue processes in the hamstring muscles with a significant reduction in voluntary activation levels, which was not apparent for the knee extensors. However, in contrast to Marshall and colleagues (2014), they also demonstrated the involvement of peripheral fatigue processes for both the quadriceps and hamstring muscles. These conflicting results for the influence of peripheral fatigue processes may be largely due to the fatigue protocol utilised in each study, namely a soccer simulation task versus a submaximal isometric knee flexor fatiguing task. Such findings warrant further investigation. Furthermore, Coratella and colleagues (Coratella et al., 2016; Coratella et al., 2018) also showed that the hamstring muscles fatigued earlier than the quadriceps muscle in both a submaximal isometric fatigue protocol at 70% MVC and a maximal effort concentric fatigue protocol. The hamstring muscles have a greater proportion of type II muscles fibres compared to the quadriceps (Garrett et al., 1984), which may explain their reduced fatigue resistance. The investigation of the onset of fatigue in the hamstring muscles compared to the quadriceps in an ACL-reconstructed population would be of particular interest, given the role of the hamstring muscle in limiting ATT. This may have implications for re-injury risk in this group.

In conclusion, there are a number of factors which can influence muscle fatigue and the subsequent changes that might be observed to be caused by central and peripheral factors. This makes investigations of muscle fatigue more challenging. The current work is not seeking to these address mechanisms. However, it will identify the extent of fatigue in the hamstring muscles 9–12 months after ACL reconstruction, which to date has not received much attention in the literature. From a clinical perspective focused upon ACL reconstruction, an appreciation of the extent of fatigue in the hamstring muscles will provide some indication as to whether it might be important to include endurance training in rehabilitation programmes. Later research might explore the contribution of central and peripheral mechanisms to hamstring muscle fatigue.

## 2.6 Hamstring Muscle Endurance in ACL-Reconstructed Knees

While restoring quadriceps and hamstring strength has been the central focus in the exercise rehabilitation process following ACL reconstruction, many sports and recreational activities require endurance capability. Without sufficient muscle endurance, fatigue can ensue and result in additional stress on the graft, potentially leading to re-injury.

Only a small number of researchers have investigated quadriceps and hamstring endurance capability following an ACL reconstruction with a hamstring graft, and the quality of these studies is variable. Tow and colleagues (2005) assessed hamstring endurance in both a bone patellar tendon bone (BPTB) graft and a hamstring graft population. The endurance testing protocol was not well documented, but involved the use of an isokinetic dynamometer at a speed of 240°/second. The findings showed that hamstring endurance measures were notably reduced compared to the uninjured leg in the hamstring graft group at 2 years post-surgery, with a mean LSI of 88%.

In two papers (Vairo, 2014; Vairo et al., 2008) hamstring endurance was investigated in an ACL-reconstructed group with a hamstring graft. The first paper (2008) assessed participants 21 months post-surgery using a maximal effort test. Participants were assessed using an isokinetic dynamometer at an angular velocity of 240°/second and were asked to complete as many maximal effort repetitions as possible in 45 seconds. Total work was not significantly different for hamstring endurance between the injured leg and either the uninjured leg or a healthy control group. The second paper (2014) assessed participants at a mean of 26 months post-surgery using a maximal effort test. In this study participants were assessed in a prone position on an isokinetic dynamometer at a speed of 240°/second and participants were again asked to complete as many maximal effort repetitions as possible in 45 seconds. Total work over this period was examined and the results showed a statistically significant difference (22%) in hamstring endurance between the injured leg and the healthy matched control group only. There was no statistically significant difference between hamstring endurance of the injured and uninjured legs.

Most recently, D. Lee and colleagues (2015) assessed hamstring endurance pre-operatively and at 6 and 12 months post-surgery in a hamstring graft group. Their protocol for assessing hamstring endurance used 15 maximal effort repetitions on an isokinetic dynamometer whilst in a sitting position at a speed of 180°/second. They found a significant difference in hamstring endurance between the involved and uninvolved legs at both 6 months (18% deficit) and 12 months (16% deficit) post-surgery.

In summary, the studies that have examined hamstring fatigue following ACL reconstruction have reported conflicting findings. Deficits in hamstring endurance of 12% to 22% have been demonstrated from 6 months to 2 years post-surgery; however, one study did not find any significant difference in hamstring endurance 21 months post-surgery. A 16% deficit in hamstring endurance has been shown at 12 months post-surgery. Testing protocols and the time point post-surgery at which testing was completed varied widely. It is interesting to note that the fatiguing exercise has been undertaken with an isokinetic dynamometer and has involved maximal effort muscle activation only. One can argue that repeated maximal effort contractions provide evidence of ability to generate maximum strength repeatedly and this is not often observed in sporting scenarios. A submaximal fatiguing exercise protocol has not been assessed and would provide more in-depth understanding of how hamstring function may change during sporting scenarios.

## 2.7 Muscle Strength after ACL Reconstruction

Although not the key focus of the current research, it should be mentioned that extensive research has been carried out investigating the effects of ACL injury and ACL reconstruction on the strength of the muscles surrounding the knee. In respect of the former, a quadriceps deficit of 4%-42% and a hamstrings strength deficit of up to 34% has been demonstrated in the ACL-deficient knee compared to the uninjured knee (Czaplicki, Jarocka, & Walawski, 2015; Hohmann et al., 2016; Hsiao et al., 2014; Keays, Bullock-Saxton, Keays, & Newcombe, 2001; H. Kim, Lee, Ahn, Park, & Lee, 2016; H. Lee, Cheng, & Liau, 2009; McNair, Marshall, & Matheson, 1990; Pincivero, Heller, & Hou, 2002; Tengman, Brax Olofsson, Stensdotter, Nilsson, & Häger, 2014; Tsepis, Vagenas, Giakas, & Georgoulis, 2004). These deficits have been shown to persist for up to 33 months post-injury.

Research conducted with ACL-reconstructed groups has occurred at differing time points post-surgery. Research has investigated quadriceps and hamstring strength, and the protocols used have varied widely across the literature. Isokinetic testing has demonstrated quadriceps strength deficits of 4%–33% up to 24 months post-surgery and hamstring strength deficits as large as 27% up to 3 years post-surgery (Aglietti, Giron, Buzzi, Biddau, & Sasso, 2004; Ardern, Webster, Taylor, & Feller, 2010a; Czaplicki et al., 2015; Elmlinger, Nyland, & Tillett, 2006; Hiemstra, Webber, MacDonald, & Kriellaars, 2007; Keays et al., 2001; J. Kim et al., 2011; Konrath et al., 2016; Kramer, Nusca, Fowler, & Webster-Bogaert, 1993; Lautamies, Harilainen, Kettunen, Sandelin, & Kujala, 2008; Machado et al., 2018; Nakamura et al., 2002; A. Thomas, Villwock, Wojtys, & Palmieri-Smith, 2013).

While it is expected that muscle strength deficits will be present in the early period of rehabilitation, by 9–12 months post-surgery many patients have been provided with clearance to return to sport and it would be expected that the involved limb would have similar strength values to those of the uninvolved limb at this time. Nevertheless, it is apparent that notable deficits in hamstring strength remain at this point. Ebert and colleagues (2018) investigated hamstring strength isokinetically at 90°/second and demonstrated a significant deficit (9%) in hamstring strength when comparing the involved and uninvolved legs at 1 year post-surgery. In contrast, Czaplicki and colleagues (2015) found no significant differences in hamstring strength at 12 months post-surgery, tested at both 60°/second and 180°/second on the isokinetic dynamometer.

When comparing the strength of the uninjured leg to that of a healthy control group, the results have been mixed. A number of researchers (Mirkov et al., 2017; Mohammadi et al., 2013; Petschnig, Baron, & Albrecht, 1998; Schmitt, Paterno, & Hewett, 2012) have not found any significant differences in quadriceps or hamstring strength between the uninjured leg and that of a healthy control up to 12 months post-surgery. In particular, Mohammadi and colleagues (2013) did not find any significant differences in the hamstring strength of the uninjured leg when compared to a healthy control group, tested at 60°/second and 180°/second at 8 months post-surgery. In contrast to these studies, Bie Larsen, Farup, Lind, and Dalgas (2015) demonstrated a significant deficit (12%–15%) between the uninjured leg and a healthy control group for hamstring strength measured both concentrically and eccentrically at 60°/second and 180°/second, 9–12 months post ACL reconstruction.

In conclusion, it is apparent that hamstring strength deficits can persist on the injured leg up to 3 years after an ACL reconstruction; however, the extent of this deficit may be dependent on the quality of rehabilitation undertaken by the individual. There are no firm conclusions regarding the strength deficit of the uninjured leg compared to a healthy control, and further research is warranted.

## 2.8 Self-Reported Measures after ACL Reconstruction

Questionnaires provide important information concerning the perceptions of the participants in respect of what are regarded as important constructs (e.g., pain, function, satisfaction, fear of re-injury) upon which rehabilitation programmes are based. Of interest in the current study was whether self-report questionnaire scores are related to hamstring muscle performance variables (e.g., endurance). Such findings provide clues to new potential ways of improving rehabilitation programmes.

The Knee Injury and Osteoarthritis Outcome Scale (KOOS) is an outcome measure commonly used after ACL reconstruction (Roos, Roos, Lohmander, Ekdahl, & Beynnon, 1998). The KOOS has five subscales which relate to pain, symptoms, activities of daily living, sports and recreational activities, and quality of life. The score from each subscale is converted to a percentage, with higher scores indicating greater function and recovery. The score from each subscale is usually reported separately, although can be reported as a total score. At 12 months after ACL reconstruction, mean values on each of the subscales have been reported as follows: pain ranges from 85% to 97%; symptoms range from 78% to 93%; function, daily living ranges from 92% to 100%; function, sports and recreational activities range from 65% to 91%; and quality of life ranges from 61% to 82% (Antosh, Svoboda, Peck, Garcia, & Cameron, 2018; Azus et al., 2018; Beischer et al., 2018; Bodkin, Goetschius, Hertel, & Hart, 2017; G. Hill & O'Leary, 2013; Magnitskaya et al., 2019; Samuelsson et al., 2017; Stańczak et al., 2018). These results indicate that at 12 months post-surgery, a time point where many individuals have returned to sport, there are still significant deficits in perceived function, especially in the domains of function, sports and recreational activities and quality of life.

Another questionnaire commonly utilised in clinical practice for knee conditions includes the Lower-Limb Task Questionnaire (LLTQ). It is particularly focused upon difficulties in performing tasks and these are delineated into two sections, one related to activities of daily living and another related to recreational activities. This questionnaire has strong psychometric properties (McNair et al., 2007), and during its development included individuals with ACL-reconstructed limbs. Additionally, due to its conciseness, it is easily and commonly utilised in the clinical environment in New Zealand.

Over the past decade there has been increased focus across the literature on the impact of an individual’s psychological status on their recovery and ability to return to their pre-injury level of sport following an ACL reconstruction. A number of psychological factors have been shown to be related to the return to sport, including fear of re-injury, poor confidence in the knee, and kinesiophobia (Ardern et al., 2014; Czuppon, Racette, Klein,

& Harris-Hayes, 2014). Questionnaires in this area with sound psychometric properties include the ACL Return to Sport after Injury (ACL-RSI) scale and the Injury - Psychological Readiness to Return to Sport (I-PRRS) scale (Glazer, 2009; Webster, Feller, & Lambros, 2008), the latter questionnaire being more widely utilised clinically due to it being a six-item questionnaire which assesses an individual's confidence in their knee in regards to a return to sport.

There are a number of researchers which have investigated the relationship between self-reported function and muscle performance following an ACL reconstruction; however, the majority have assessed the relationship between quadriceps strength and perceived function. Only a small number of researchers have investigated the relationship between hamstring muscle performance and perceived function. Additionally, there are no studies to date which have investigated the relationship between knee muscle strength or endurance and the LLTQ or I-PRRS questionnaire in an ACL-reconstructed population.

One study (Bodkin et al., 2017) investigated the relationship between self-reported function and both quadriceps and hamstring endurance during eight repetitions performed at maximal effort. One could argue that this is therefore measuring maximal strength over eight repetitions, rather than muscle endurance capability. This study divided the participants into three different groups: an early group (9 months to 2 years post-surgery); a middle group (2–5 years post-surgery); and a late group (5–15 years post-surgery). It also included participants with both a BPTB graft and a hamstring tendon graft. With regard to hamstring endurance, a small and significant correlation was found between hamstring work done and the KOOS quality of life subscale ($r = 0.34$). When analysing participants in the early group only (mean of 17.1 months post-surgery), and who had received a hamstring tendon graft only, a strong and significant correlation was found between absolute hamstring work done and the KOOS quality of life subscale ($r = 0.717$). These authors found no significant relationship between quadriceps work done and any subscale of the KOOS ($r = 0.08$–$0.23$).

When considering the relationship between hamstring strength and self-reported measures, Bodkin and colleagues (2017) found a small and significant relationship between hamstring strength (normalised to weight and height) and the KOOS quality of life subscale ($r = 0.32$). However, when considering the early group only (mean 17.1 months post-surgery), and those with a hamstring graft only, a large and significant correlation was found between hamstring peak torque and the KOOS sports and recreational activities subscale ($r = 0.788$, $p = 0.012$) (Bodkin et al., 2017). These results have been supported by a more recent study (Harput, Ozer, Baltaci, & Richards, 2018) where a small to moderate positive and significant correlation has been demonstrated between hamstring strength following an ACL reconstruction with a hamstring tendon graft and the following subscales of the KOOS: symptoms (r = 0.35–0.53); pain (r = 0.32–0.47); function, sports and recreational activities (r = 0.47–0.53); and quality of life (r = 0.43–0.45).

There are few studies to date which have investigated the relationship between psychological readiness to return to sport and muscle performance in an ACL-reconstructed population. A small but significant correlation has been demonstrated between hamstring strength and the ACL-RSI 9 months after an ACL reconstruction (r = 0.14) (O'Connor, Falvey, King, Richter, & Webster, 2020). The same study did not find a significant relationship between the ACL-RSI and hamstring LSI (r = 0.05), or ACL-RSI and quadriceps strength (r = 0.04–0.06). In contrast to these findings, an earlier study by Lepley, Pietrosimone, and Cormier (2018) demonstrated a strong and significant positive correlation between quadriceps strength and the ACL-RSI 28 weeks after an ACL reconstruction (r = 0.6). The discrepancy in results for quadriceps strength may be due to the difference in follow-up time and also the difference in the quadriceps strength parameters utilised across the studies.

Self-reported measures have not traditionally been included in return-to-sport decision making. However, there is increasing discussion and inclusion of these measures across the literature (Gokeler, Welling, Zaffagnini, Seil, & Padua, 2017; Toole et al., 2017; Welling et al., 2018). More recently, the importance of considering an athlete's anxiety and fear surrounding re-injury has been explored, and attention given to the various strategies/tools, both intrinsic and extrinsic, which can be implemented as part of the rehabilitation programme to help facilitate a return to pre-injury level of sport (Mahood, Perry, Gallagher, & Sole, 2020). A test battery for assessing an individual's readiness to return to sport, inclusive of self-reported measures, has been investigated and has utilised the International Knee Documentation Committee (IKDC) questionnaire and the ACL-RSI (Gokeler, Welling, Zaffagnini, et al., 2017; Welling et al., 2018). An IKDC score within the 15$^{th}$ percentile for healthy subjects and an ACL-RSI score of greater than 56 were considered normal in these studies. At 9.5 months post-surgery, Welling and colleagues (2018) showed that the number of participants passing the criteria for normal function on the IKDC and the ACL-RSI was 63% and 73% respectively. With regard to psychological readiness to return to sport, Ardern, Taylor, Feller, Whitehead, and Webster (2013) showed that two factors are predictive of returning to ones pre-injury level of sport 12 months after surgery, namely a higher score on the ACL-RSI prior to surgery, and a lower self-predicted time for return to pre-injury level of sport prior to surgery. At 4 months post-surgery, Ardern et al. (2013) found that the ACL-RSI score, the Tampa Scale of Kinesiophobia (TSK) score and the Sport, Rehabilitation and Locus of Control (SRLC) score all predicted return to pre-injury sport at 12 months post-surgery with 86% accuracy.

In summary, self-reported measures are an important tool to understand an individual's perceived function, and this is particularly important when decision making regarding the return to sport following an ACL reconstruction is occurring. The inclusion of questionnaires pertaining to psychological readiness to return to sport is likely an important factor in this population, and the evidence suggests that there are persistent deficits in both self-perceived function and psychological readiness to return to sport measures at 9–12 months after an ACL reconstruction. Given the importance of muscle endurance capability for sport, understanding the relationship between knee muscle endurance and these self-reported measures is important. Although there is limited research investigating the relationship between hamstring muscle endurance and perceived function, there is evidence to support a relationship between these variables during maximal effort hamstring muscle testing across a hamstring graft group and a mixed graft group of participants. Further research investigating the relationship between submaximal hamstring endurance and self-reported function at 9–12 months post-surgery, separating for different graft types, would provide greater insight into the relevance of these relationships at a time point when individuals are considering returning to sport, and therefore the consideration of their use in return-to-sport decision making can be made with more confidence.

## 2.9 Hop Tests in ACL Reconstruction

Functional performance tests (e.g., the single hop for distance, triple hop for distance, crossover hop for distance, side hop, vertical jump, and 6m timed hop test) have been widely used across the literature as outcome measures to assess function, and as criteria for the return to sport in an ACL-reconstructed population (Bie Larsen et al., 2015; Gustavsson et al., 2006; Narducci, Waltz, Gorski, Leppla, & Donaldson, 2011). Most commonly, hop symmetry between legs is reported as an LSI score. For the hop for distance tests, the LSI is calculated as follows: (involved leg distance/uninvolved leg distance) multiplied by 100, and reported as a percentage based on the uninvolved leg value (Grindem et al., 2011; Noyes, Barber, & Mangine, 1991).

A series of hop tests as a means to investigate lower limb function was first described in the literature by Barber, Noyes, Mangine, McCloskey, and Hartman (1990) for both a normal and an ACL-deficient population. They investigated the single hop for distance, 6m timed hop, and vertical jump. Within a normal population, they found that 92% and 93% of the population scored an LSI of 85% or greater for the single hop for distance and the timed hop respectively. There was much greater variance among LSI scores for the vertical jump; however, based on these results, they used 85% as their cut off score to indicate a normal LSI for these three hop tests. Across an ACL-deficient population, they found a significant difference across all hop test measures when comparing the uninvolved leg and involved leg of the group. They also found a significant difference between LSI scores for a normal population and an ACL-deficient population (Barber et al., 1990). In 1991, this same group (Noyes et al., 1991) published a second study investigating hop tests in an ACL-deficient population. This study utilised four different hop tests: the single hop for distance, the triple hop for distance, the crossover hop for distance and the 6m timed hop. In this study, they demonstrated that 53% of their ACL-deficient participants scored abnormally on three or four of the hop tests with regard to LSI scores (Noyes et al., 1991). This battery of tests has been investigated on numerous occasions since then, in both ACL-deficient and ACL-reconstructed populations, by numerous authors and working groups, particularly over the past decade (Ebert et al., 2018; Grindem, Snyder-Mackler, Moksnes, Engebretsen, & Risberg, 2016; Logerstedt et al., 2014; Logerstedt et al., 2012; Logerstedt, Lynch, Axe, & Snyder-Mackler, 2013; Myers, Jenkins, Killian, & Rundquist, 2014; Reinke et al., 2011; Schmitt et al., 2012; Toole et al., 2017; Wellsandt, Failla, & Snyder-Mackler, 2017; Wilk, Romaniello, Soscia, Arrigo, & Andrews, 1994).

As mentioned above, a cut-off of greater than 85% LSI has been reported in the literature as determining normal function with regard to both strength and hop test measures (Ardern, Taylor, Feller, & Webster, 2013; Barber et al., 1990; Noyes et al., 1991; Wilk et al., 1994). However, over the past decade, an LSI of greater than 90% has been widely accepted as a more appropriate cut-off score for these measures, including their use in return-to-sport decision making. It is thought to better discriminate between those who have restored normal function post-surgery and those who have not (Ebert et al., 2018; Fitzgerald, Axe, & Snyder-Mackler, 2000; Gokeler, Welling, Benjaminse, et al., 2017; Grindem et al., 2016; Gustavsson et al., 2006; Hartigan, Axe, & Snyder-Mackler, 2010; Kyritsis et al., 2016; Logerstedt et al., 2013; Schmitt et al., 2012; Thomeé et al., 2011; Thomeé et al., 2012; Welling et al., 2018; Wellsandt et al., 2017).

Gustavsson and colleagues (2006) investigated a different group of hop tests to those utilised by Barber et al. (1990) in both an ACL-deficient group and an ACL-reconstructed group. They used a test battery including the single hop for distance, vertical jump and side hop. They showed a significant difference between the involved and uninvolved leg for all three hop tests in both an ACL-deficient population and an ACL-reconstructed population at a mean of 6 months post-surgery. When analysing hop test scores as an LSI, for reconstructed patients they reported a mean LSI of 76% for the vertical jump, 86% for the single hop for distance, and 80% for the side hop (Gustavsson et al., 2006). They concluded that this battery of hop tests is able to differentiate between the hop performance of the injured and uninjured leg in an ACL-reconstructed population (Gustavsson et al., 2006).

A number of researchers (Bie Larsen et al., 2015; de Fontenay, Argaud, Blache, & Monteil, 2015; Gokeler, Welling, Benjaminse, et al., 2017; Logerstedt et al., 2013; Thomeé et al., 2012) have shown a significant difference in hop performance between the injured leg and uninjured leg in an ACL-reconstructed population, in favour of the uninjured leg. An initial study by Thomeé and colleagues (2012) demonstrated significant differences in hop performance between the injured and uninjured leg (in favour of the uninjured leg) at 12 and 24 months post-surgery in both BPTB graft and hamstring graft groups. They investigated the vertical jump, single hop for distance and the side hop tests, and reported a 12%, 6% and 13% deficit respectively at 12 months post-surgery. A later study by Bie Larsen and colleagues (2015) found a mean deficit of 19% for the single hop for distance between the involved and uninvolved legs 9–12 months post-surgery. Participants in this study had either a BPTB graft or a hamstring graft.

When comparing the hop performance of the uninjured leg with a healthy control group, the results are conflicting. Some authors (Mohammadi et al., 2013; Schmitt et al., 2012) found no significant differences between the hop performance of the uninjured leg and a healthy control group for the single hop for distance, triple hop for distance and crossover hop for distance 7–8 months after an ACL reconstruction with either a BPTB or hamstring graft. This was confirmed for the single hop for distance and triple hop for distance at 12 months post-surgery with a BPTB graft (Petschnig et al., 1998). In contrast, de Fontenay and colleagues (2015) found a significant difference for the single hop for distance and triple hop for distance between the uninjured leg and a healthy control group (16% and 19% respectively) at a mean of 7 months post-surgery with a BPTB graft. Bie Larsen and colleagues (2015) demonstrated similar results 9–12 months post-surgery in a mixed graft cohort. They demonstrated an 18% deficit in single hop for distance scores between legs. Some of the variance in results between studies may be due to the sample size, as the number of participants in the studies by both Bie Larsen and colleagues (2015) and de Fontenay and colleagues (2015) were small, with 16/16 and 13/16 for the ACL-reconstruction/control groups respectively.

There is some evidence to suggest that the structure of the rehabilitation programme may be an important factor in the patient's outcome with regard to functional performance testing at 12 months post-surgery. Ebert and colleagues (2018) graded each participant's rehabilitation based on: the level of supervision; how long the rehabilitation lasted post-surgery; whether or not structured jumping, landing or agility exercises were performed; and whether or not the return to training or sport was supervised. They showed that the level of rehabilitation was significantly associated with LSIs for all hop tests and both quadriceps and hamstring peak torque ($r = 0.28$ to $0.68$; $p \leq 0.003$). Those participants whose rehabilitation was supervised for 6 months or longer and included structured jumping, landing and agility drills, with either independent or supervised return to structured gym exercise, and independent or supervised return to training and sport, scored greater than 90% on all four hop tests and on both quadriceps and hamstring peak torque measures. Further research in this area is needed to be able to draw firm conclusions regarding the importance of structured rehabilitation on outcomes following an ACL reconstruction.

The relationship between hamstring strength and hop test performance has been investigated in both a healthy and ACL-reconstructed population. Hamilton, Shultz, Schmitz, and Perrin (2008) showed a significant and strong positive correlation between hamstring peak torque at both 60°/second and 180°/second and both the triple hop for distance ($r = 0.75$) and the vertical jump ($r = 0.75$) in a healthy population. In an ACL-reconstructed cohort, Lautamies and colleagues (2008) found a small but statistically significant relationship between the single hop for distance and hamstring strength in a BPTB graft group at both 60°/second and 180°/second ($r = 0.29$ and $0.27$ respectively) and a hamstring graft population at 180°/second ($r = 0.24$). In this study, participants were a median of 5 years post-surgery (range 3 years 7 months to 6 years 3 months). More relevant to the current study, Ko, Yang, Ha, Choi, and Kim (2012) demonstrated a significant negative and moderate correlation between the hamstring strength deficit and the single hop for distance at both 12 months ($r = -0.312$) and 24 months ($r = -0.354$) post-surgery. This has been supported elsewhere with the demonstration of a moderate and significant negative correlation between hamstring strength deficit and the single hop for distance in a hamstring graft group ($r = -0.43$) at a mean of 32 months post-surgery (J. Kim et al., 2011). To date there are no studies which report the relationship between functional performance hop tests and hamstring muscle endurance.

There is limited research investigating the impact of fatigue on hop performance in an ACL-reconstructed population, and this research has considered quadriceps fatigue only. Augustsson and colleagues (2004) recruited a cohort of male participants at a mean of 11 months after an ACL reconstruction who all demonstrated an LSI of greater than 90% on the single hop for distance under non-fatigued conditions. Participants with a mixture of both BPTB and hamstring grafts were included. Quadriceps fatigue was elicited on a leg extension machine where participants were asked to complete repeated repetitions at 50% of their one repetition maximum until failure. The single hop for distance was repeated immediately after failure on the leg extension machine. An LSI of greater than 90% was not achieved by 68% of participants under fatigued conditions. The mean LSI for the single hop for distance was 97% pre-fatigue and reduced to 89% post-fatigue (Augustsson et al., 2004). A later study by this same group of researchers (Augustsson et al., 2006) also showed a significant decrease in hop performance for the single hop for distance after a quadriceps fatiguing exercise in a healthy population. They demonstrated a 20% and 11% decrease in hop performance post-fatigue during a knee extension exercise at 50% and 80% of one repetition maximum respectively. This work further supports the impact of fatigue on hop performance.

In summary, hop performance tests are an important tool to determine whether individuals have restored normal function following an ACL reconstruction, and are particularly important in return-to-sport decision making. However, it is clear that at 12 months post-surgery, persistent deficits exist in this cohort, and the type of rehabilitation and level of supervised rehabilitation may be an influencing factor. Muscle fatigue has a negative impact on hop performance, and this is an important consideration for the use of hop tests in return-to-sport decision making, as the majority of injuries occur in the final stages of a sporting event or game, when players are fatigued. However, the influence of hamstring fatigue on hop performance is unknown.

### 2.10 Return to Sport after ACL Reconstruction

The return to sport after an ACL reconstruction is an area which has received significant attention in both the literature and amongst expert clinicians internationally. To date, there is no consensus on the exact measures, either self-reported or objective measures, which should be utilised to help guide this decision-making process. A systematic review by Barber-Westin and Noyes (2011) identified the large inconsistencies which exist when clinicians are choosing appropriate criteria to guide return-to-sport decision making. There was a failure to mention any specific return-to-sport criteria following an ACL reconstruction in 40% of included studies. Of those studies that did mention specific return-to-sport criteria, 60% mentioned the time post-operatively as a criterion for the return to sport, with 32% identifying 6 months post-surgery as an appropriate timeframe.

Objective measures were mentioned as criteria for the return to sport in 14% of the included studies, with only 9% mentioning strength measures and 4% mentioning the single hop for distance (Barber-Westin & Noyes, 2011). Despite these inconsistencies, it has been widely accepted in recent years that utilising a battery of outcome measures and tests to assist in the decision-making process is preferable to any single test in isolation (Fitzgerald et al., 2000; Gokeler, Welling, Zaffagnini, et al., 2017; Grindem et al., 2016; Gustavsson et al., 2006; Kyritsis et al., 2016; Thomeé et al., 2011).

Both quadriceps and hamstring strength measures have been considered as part of the decision-making process for the return to sport after an ACL reconstruction (Gokeler, Welling, Zaffagnini, et al., 2017; Jang, Kim, Ha, Wang, & Yang, 2014; Thomeé et al., 2011; Toole et al., 2017; Welling et al., 2018); however, more emphasis has been placed on quadriceps strength across the literature (Grindem et al., 2016; Hartigan et al., 2010; Kyritsis et al., 2016). Neither quadriceps nor hamstring endurance has been considered to date. The use of functional performance hop tests in an ACL-reconstructed population has gained increasing popularity over the past decade, particularly regarding their use in return-to-sport decision making post-surgery (Abrams et al., 2014; Ebert et al., 2018; Gokeler, Welling, Zaffagnini, et al., 2017; Logerstedt et al., 2014). It is now also widely accepted that a battery of hop tests is superior to a single hop test in isolation for assessing one's readiness for returning to sport post-surgery (Fitzgerald et al., 2000; Gustavsson et al., 2006; Kyritsis et al., 2016; Thomeé et al., 2011).

The European Board of Sports Rehabilitation (EBSR) (Thomeé et al., 2011) has made recommendations for return-to-sport decision making which are dependent on the type and level of sport that the patient is returning to play. If returning to a pivoting, contact and/or competitive sport, they recommend an LSI of 100% for both knee extensor and flexor strength, as well as 90% LSI on two maximum single leg hop tests (e.g., single hop for distance, and vertical jump) and one multiple single leg hop test (e.g., side hop, or triple hop for distance). If returning to a non-pivoting, non-contact and recreational sport, they recommend an LSI of 90% or greater for knee extensor and flexor strength, and a 90% LSI on either one maximum single leg hop test or one endurable single leg hop test.

The number of participants passing the 90% LSI cut-off for strength and hop test measures varies greatly across the literature, and the results are surprisingly poor. It has been reported that the percentage of participants passing the cut off of greater or equal to 90% LSI for quadriceps strength ranges from 8%–70% at 6 months post-surgery (Gokeler, Welling, Zaffagnini, et al., 2017; Welling et al., 2018; Wellsandt et al., 2017), 44% at 8 months post-surgery (Toole et al., 2017), and 53%–60% at 9 months post-surgery (Welling et al., 2018) across mixed graft cohorts. At 12.5 months post-surgery with a hamstring graft, only 31% of participants had passed the 90% cut off for quadriceps LSI (Ebert et al., 2018). With regards to hamstring strength, the percentage of participants achieving an LSI of greater or equal to 90% across mixed graft cohorts ranges from 54%–81% at 6 months post-surgery (Gokeler, Welling, Zaffagnini, et al., 2017; Welling et al., 2018), 65% at 8 months post-surgery (Toole et al., 2017), and 73%–86% at 9 months post-surgery (Welling et al., 2018). At 12.5 months post-surgery with a hamstring graft, 55% of participants had achieved an LSI of 90% or greater for hamstring strength (Ebert et al., 2018). The variability across these results is likely due to differences related to rehabilitation, components of the return-to-sport test, and the type of graft received. Additionally, there were notable differences in sample size (ranging from 28 to 115), and mean age (ranging from 17 to 27 years) across these studies.

With regards to the hop tests, at 6 months post-surgery with either a BPTB or hamstring graft, the percentage of participants achieving an LSI of greater than 90% has been shown to range from 53%–79% for the single hop for distance, 54% for the crossover hop for distance, 86% for the triple hop for distance and 50% for the side hop (Gokeler, Welling, Zaffagnini, et al., 2017; Wilk et al., 1994). At 7 months post-surgery with either a BPTB or hamstring tendon graft, the percentage of participants achieving an LSI of greater than 90% was shown to be 83% for the single hop for distance and 87% for the triple hop for distance (Gokeler, Welling, Benjaminse, et al., 2017). At a mean of 12.5 months post-surgery in a hamstring graft cohort, Ebert and colleagues (2018) reported that the percentage of participants achieving an LSI of greater than 90% for the hop tests were as follows: 47% for the single hop for distance and 6m timed hop, 55% for the triple hop for distance and 51% for the crossover hop for distance. In this study, the level of supervised rehabilitation undertaken by participants was variable. In contrast to these results, Ardern, Taylor, Feller, Whitehead, and Webster (2013) reported much more favourable results in a hamstring graft cohort at the same time point, but with a cut-off for return-to-sport clearance of 85% LSI. This cut-off was passed by 84% of participants for both the single hop for distance and crossover hop for distance. Participants in this study were also required to complete a supervised rehabilitation programme. Both of these factors, namely the level of supervised rehabilitation and LSI cut-off utilised, may have influenced the discrepancy in scores between these studies.

Rather than reporting on the percentage of participants achieving an LSI of greater than 90% after an ACL reconstruction, some authors (Ardern, Taylor, Feller, Whitehead, et al., 2013; Ebert et al., 2018; Thomeé et al., 2012) reported on the mean LSI scores for each of the hop tests analysed at 12 months post-surgery. Thomeé and colleagues (2012) reported their mean LSI scores for each of the hop tests as follows: 94% for the single hop for distance; 88% for the vertical jump; and 87% for the side hop. Ardern, Taylor, Feller, Whitehead, et al. (2013) reported a mean LSI score of 94% for the single hop for distance and 99% for the triple hop for distance. In a later study, Ebert and colleagues (2018) reported the following mean LSI scores: 86% for the single hop for distance, 6m timed hop, and crossover hop for distance; and 87% for the triple hop for distance. With regard to the single hop for distance and triple hop for distance, Thomeé et al. (2012) and Ardern, Taylor, Feller, Whitehead, et al. (2013) had much more favourable results across these tests than the study by Ebert and colleagues (2018). Participants in the study by Thomeé et al. completed a standardised rehabilitation programme which may have been a factor in their superior results. This is in contrast to the studies by Ardern, Taylor, Feller, Whitehead, et al. and Ebert et al, where there was no requirement for a supervised rehabilitation programme to be undertaken. However, it is thought that one of the factors which may have influenced the superior results in the study by Ardern, Taylor, Feller, Whitehead, et al. (2013) was the lack of exclusion of previous ACL injury or reconstruction for either limb in the study cohort, which may have had a profound effect on their LSI scores. The graft type utilised may also have influenced the results, with Ebert and colleagues (2018) including a hamstring graft cohort only, in comparison to the two other studies which had mixed cohorts of both BPTB and hamstring grafts (Ardern, Taylor, Feller, Whitehead, et al., 2013; Thomeé et al., 2012).

The time point post-surgery at which the return to sport occurs following an ACL reconstruction can influence an individual's risk of re-injury greatly and has become an area of interest in the literature in recent years. It has been shown (Grindem et al., 2016) that all participants who returned to sport less than 5 months after an ACL reconstruction sustained a new injury to either their involved or uninvolved leg within 2 months of the return to sport. These authors also demonstrated that for every month up until the ninth month post-surgery for which the return to sport was delayed, there was a 51% reduction in re-injury risk (Grindem et al., 2016). As outlined above, it is widely understood that achieving an LSI of greater than 90% for strength and hop test measures is indicative of restoration of near normal function in the reconstructed limb and therefore an important factor in reducing re-injury risk with the return to sport. However, a recent meta-analysis by Webster and Hewett (2019) reported some interesting findings. When considering all possible knee injuries, they found there was no significant reduction in the risk of re-injury for those who passed the return-to-sport test battery (RR = 0.80, (95% CI 0.27–2.3), $p = 0.7$). They did, however, report that passing the return-to-sport test battery did significantly reduce the risk of re-injury to the graft (RR = 0.40, (95% CI 0.23–0.69), $p < 0.001$). Of most interest was their finding that passing the return-to-sport test battery significantly increased the risk of a contralateral ACL injury (RR = 3.35 (95% CI 1.52–7.37), $p = 0.003$) (Webster & Hewett, 2019). It should be noted that the cut-off score for LSI was variable and in one study included in the meta-analysis it was not reported. These results add to the conflicting conclusions regarding an appropriate return-to-sport test battery and its's usefulness in minimising the risk of re-injury to either knee. Further research in this area is required.

In summary, to date there is no agreement internationally on a specific return-to-sport assessment test for individuals following an ACL reconstruction; however, there is agreement that a battery of tests is superior to any one test in isolation. Quadriceps and hamstring strength, as well as hop performance, have been considered widely across the literature as important aspects of this assessment. However, to date the inclusion of quadriceps or hamstring endurance capability has not been discussed widely. Similarly, less attention has been paid to the inclusion of performance-based function under fatigued conditions. These aspects of muscle function and hop performance are areas requiring further empirical evidence. Consideration of a test battery which will help to reduce the risk of ACL injury to the contralateral limb is also worthy of attention in a population where the contralateral ACL injury risk is high.

# Chapter 3 Methodology

## 3.1 Introduction

The principal aims of this study were to investigate whether or not individuals who have undergone an ACL reconstruction with an ipsilateral hamstring graft have reduced hamstring endurance on their injured leg compared to their uninjured leg, and on their uninjured leg compared to a group of age-, gender- and activity-matched controls, 9–12 months post-surgery. This study also investigated the relationship between knee function (using both written questionnaires and performance-based hop tests) and the hamstring endurance of the injured leg. Finally, the performance during the hopping tests of the injured leg was compared to the uninjured leg and the leg of a healthy matched control group and two of these hop tests were also re-evaluated under fatigued conditions.

## 3.2 Study Design

A cross-sectional inter-limb comparison study was utilised. This involved an assessment of participants' knee function at one time point only, 9–12 months after an ACL reconstruction utilising a hamstring graft. Participants in the ACL-injured group completed all tests on both legs. The healthy age-, gender- and activity-matched controls completed testing on one leg only, which was matched for dominance to the uninjured leg of the ACL group.

The research methodology and study protocol were reviewed and approved by the Auckland University of Technology Ethics Committee (approval number 17/423 – see Appendix A). All participants received and were given the opportunity to read an information sheet containing details of the study (see Appendix D). All participants read and signed a consent form at the beginning of their testing session, prior to participation in the study (see Appendix C).

## 3.3 Selection of Participants

### *3.3.1 Participant Recruitment*

Participants were recruited via advertisements on noticeboards in local gymnasiums, universities, and physiotherapy practices across the North Shore, Auckland. Contact was made with local sports clubs, and advertisements were distributed via email within those clubs. Participants in the injured group were also referred by local orthopaedic surgeons practising in the area. The advertisements requested participants between the ages of 20 and 55 years who had undergone an ACL reconstruction with an ipsilateral hamstring graft, 9–12 months after surgery, and also requested participants without any history of knee injury or surgery (see Appendix B).

The sample size was determined using G*Power. Sample size calculations were based on analysis from a previous study by Vairo and colleagues (2014) as well as a pilot study in the AUT Biomechanics Lab. Based upon an alpha value of 0.05 and a beta value of 0.80, for a 15% difference in mean scores associated with hamstring fatigue (work done, repetitions performed and time), 22 participants were required in each group.

Participants made initial contact with the primary researcher via phone or email. Each participant was then contacted by the researcher to screen for inclusion and exclusion criteria. Further screening was undertaken on the day of testing.

### *3.3.2 ACL Group*

Inclusion criteria:

- Had undergone an ACL reconstruction with an ipsilateral hamstring graft in the 9 to 12 months prior to assessment
- Aged between 20 and 55 years
- Understood written and spoken English

Exclusion criteria:

- Previous notable knee injury in the contralateral leg including previous surgery
- Previous notable knee injury in the ACL-reconstructed leg, including previous surgery
- History of recurring hamstring injury on either leg
- History of low back pain with radicular symptoms or signs of radiculopathy in the 6 months prior to assessment

- Presence of a neurological illness or cardiovascular disease
- High blood pressure for which medication has been prescribed
- Uncontrolled respiratory conditions (mild asthma excluded)
- Any medical condition or physical impairment which may have limited performance or put the participant at risk during testing
- Inability to provide informed consent

### *3.3.3 Control Group*

Inclusion criteria:

- Aged between 20 and 55 years
- Understood written and spoken English

Exclusion criteria:

- Previous notable knee injury in either leg, including previous surgery
- History of recurring hamstring injury on either leg
- History of low back pain with radicular symptoms or signs of radiculopathy in the 6 months prior to assessment
- Presence of a neurological illness or cardiovascular disease
- High blood pressure for which medication has been prescribed
- Uncontrolled respiratory conditions (mild asthma excluded)
- Any medical condition or physical impairment which may have limited performance or put the participant at risk during testing
- Inability to provide informed consent

## 3.4 Procedures

All testing was performed at the Biomechanics Lab of the School of Clinical Sciences, Auckland University of Technology (AUT) North Shore Campus. All subjects were tested by the principal investigator.

Upon arrival, participants completed their consent forms prior to testing. During a single two-hour testing session, participants completed questionnaires, had anthropometric data recorded, and completed a series of performance-based single leg hop tests, a strength assessment of their quadriceps and hamstring muscles on the Biodex isokinetic dynamometer, a hamstring endurance test on the Biodex isokinetic dynamometer, and a series of performance-based single leg hop tests under fatigued conditions.

### *3.4.1 Functional Questionnaires*

Participants in the ACL group completed a number of questionnaires relating to activity levels pre- and post-surgery, current function, and psychological readiness to return to sport, including the Lower-Limb Task Questionnaire (LLTQ) (see Appendix G), the Knee Injury and Osteoarthritis Outcome Score (KOOS) (see Appendix F), elements of the Cincinnati Knee Rating System (Sports Activity Scale, Activities of Daily Living Function Scales, Sports Function Scales) (see Appendix H), and the Injury-Psychological Readiness to Return to Sport Scale (I-PRRS) (see Appendix I). Participants also completed a pre-prepared questionnaire relating to demographic, surgical, rehabilitation and return-to-sport assessment details (see Appendix E). The psychometric properties of these questionnaires are described below.

The KOOS has been shown to be a reliable and valid tool for measuring knee function in an ACL-reconstructed population with intra-class correlation coefficients (ICCs) of 0.75–0.93 for the different sections of the questionnaire (lower 95% confidence intervals (CIs) of 0.73–0.91) (Roos et al., 1998; Salavati, Akhbari, Mohammadi, Mazaheri, & Khorrami, 2011). It is divided into five distinct sections that report on symptoms (including stiffness), pain, function activities of daily living, function sports and recreational activities and knee related quality of life. Each question is scored using a Likert Scale with five options for each question. Participants were asked to rate their response to each question based on their experience of their knee over the past week. If they were unsure about how to answer the question, they were asked to give the best estimate that they could. The score for each section was calculated as the sum of scores in that section. Each section was scored separately, as it is thought that it is important to interpret each section separately (Roos et al., 1998). The score from each section was transformed into a number from 0 to 100, with 0 representing severe knee problems, and 100 representing no knee problems (see Appendix F).

The LLTQ is a valid and reliable tool for measuring knee function after knee injury with ICCs of 0.96 and 0.98 for the different sections of the scale (lower 95% CIs of 0.93 and 0.97) (McNair et al., 2007). It is separated into two different sections, one relating to activities of daily living, and one relating to recreational activities. There are 10 questions in each section, relating to one’s ability to carry out a particular task. The response to each question is scored using a Likert Scale, with answers ranging from ‘Unable’ (= 0) to ‘No Difficulty’ (= 4) for ability to perform a task. Participants were asked to score each task based on their ability in the past 24 hours. If they had not completed the task in the past 24 hours, they were asked to provide their best estimate. Each section has a possible score range from 0 (maximum incapacity) to 40 (normal function) (see Appendix G).

The I-PRRS is a valid and reliable tool for measuring psychological readiness to return to sport (Glazer, 2009). It is a six-item scale used to rate a participant’s confidence to return to full sport participation after a sports injury. Each item is scored from 0 to 100 (0 = no confidence at all; 50 = moderate confidence; 100 = complete confidence) in intervals of 10. The total score is determined by calculating the sum of all six items and dividing this by 10. A total score of 60 implies complete confidence, a total score of 40 implies moderate confidence, and a total score of 20 implies poor confidence to return to full sport participation (see Appendix I).

The Cincinnati Knee Rating System has been shown to be reliable in a knee injury population with ICCs of 0.71–1.0 for the different sections of the scale (Barber-Westin, Noyes, & McCloskey, 1999). The section covering the Sports Activity Scale, Activities of Daily Living Function Scales and Sports Function Scales asks participants to rate their level of physical activity both prior to their knee injury and at their current level. It also asks them to rate their change in sports activities as a result of their injury, and their level of difficulty with a range of daily and sporting activities (see Appendix H).

### *3.4.2 Performance-Based Hop Tests*

A series of five single leg hop tests was completed by each participant including the single hop for distance, the triple hop for distance, the crossover hop for distance, the side hop, and the vertical jump for height. The hop tests were administered in line with the protocols of Reid, Birmingham, Stratford, Alcock, and Giffin (2007) and Gustavsson and colleagues (2006). The order of testing was randomised using a computer-generated randomisation programme. For all tests except the side hop, two to three practice jumps were allowed on each leg prior to the formal test. The practice jumps followed by the formal jumps were completed on the uninjured leg first, followed by the practice jumps and the formal jumps on the injured leg. Participants were asked to complete three formal jumps and the best score was recorded. A two-minute rest was provided for each leg between each different hop test. A short break, usually no longer than 30 seconds, was provided between practice trials and formal trials for each hop test. For the side hop, participants were given one short practice trial to familiarise them with the test. After a short rest, typically 30 to 60 seconds, the formal test was completed once only. The details concerning specific hops/jumps are provided below. All hop tests were completed in bare feet for consistency between participants.

*3.4.2.1 Single Hop for Distance*

The single hop for distance is a valid and reliable tool for measuring function and as a criterion for the return to sport in an ACL-reconstructed population (Reid et al., 2007) with an ICC of 0.92 (lower 95% confidence interval (CI) of 0.87). It has also been shown to be reliable in a healthy population with an ICC of 0.98, and under fatigued conditions in a healthy population with ICCs of 0.75–0.91 (Augustsson et al., 2006).

Participants were asked to stand on their uninjured leg behind a clearly marked starting line, with their great toe just behind the line. There was no restriction placed on arm movements during the test. Participants were asked to hop as far as possible, landing on the same leg only. The following criteria were required to deem a hop successful: no additional hop upon landing; no contact with the floor of either the opposite leg or either upper limb; and balance maintained for two seconds upon landing. The distance hopped was measured from the great toe at the starting point, to the heel upon landing. Once all hops were completed on the uninjured leg, the practice trials and formal hops were repeated on the injured leg in the manner described above.

*3.4.2.2 Triple Hop for Distance*

The triple hop for distance is a valid and reliable tool for measuring function and as a criterion for the return to sport in an ACL-reconstructed population with an ICC of 0.88 (lower 95% CI of 0.8) (Reid et al., 2007). It has also been shown to be correlated with hamstring peak torque in a healthy population ($r = 0.75$) (Hamilton et al., 2008).

Participants were asked to stand on their uninjured leg behind a clearly marked starting line, with their great toe just behind the line. There was no restriction placed on arm movements during the test. Participants were asked to perform three consecutive hops as far as possible, hopping on the same leg, and landing the final hop on the same leg. The same criteria as outlined for the single hop for distance were required to deem the hop successful. The distance hopped was measured from the great toe at the starting point, to the heel upon landing. Once completed on the uninjured leg, the triple hop for distance was repeated on the injured leg.

*3.4.2.3 Crossover Hop for Distance*

The crossover hop for distance has been shown to be a reliable and valid tool for measuring function and as a criterion for the return to sport in an ACL-reconstructed population with an ICC of 0.84 (lower 95% CI of 0.74) (Reid et al., 2007).

Participants were asked to stand on their uninjured leg behind a clearly marked starting line, with their great toe just behind the line. There was no restriction placed on arm movements during the test. Participants were asked to perform three consecutive hops as far as possible, hopping on the same leg, and crossing over the centre strip on each hop, landing the final hop on the same leg. The same criteria as outlined for the single hop for distance was required to deem the hop successful. The centre strip measured 15cm in width. The distance hopped was measured from the great toe at the starting point, to the heel upon landing. If testing the right leg, the participant stood to the left of the centre strip, making the first hop across the strip to the right. If testing the left leg, the participant stood to the right of the centre strip, making the first hop across the strip to the left. Once completed on the uninjured leg, the crossover hop for distance was repeated on the injured leg.

*3.4.2.4 Side Hop*

The side hop has been shown to be reliable in a healthy population with an ICC of 0.87 (95% CI: 0.75–0.94) (Gustavsson et al., 2006). Participants were asked to stand on their uninjured leg with their hands behind their back. They were asked to hop from side to side across two parallel strips of tape, placed 40cm apart on the floor, hopping as many times as possible in 30 seconds. The number of successful hops completed, without touching the tape with their foot, was recorded. Participants were allowed to touch the tape, but this was recorded as an error. If more than 25% of their hops were recorded as errors, they had to repeat the test after a three-minute rest. Prior to the formal test, participants were allowed a practice trial over a self-selected number of repetitions, until they were happy they had mastered the technique. If required, a rest break was provided between the practice trial and the formal test, typically no more than 30–60 seconds. The formal test was only completed once, unless required on a second occasion due to exceeding the threshold for acceptable errors (> 25%). Once completed on the uninjured leg, the side hop was repeated on the injured leg.

*3.4.2.5 Vertical Jump*

The vertical jump has been shown to be reliable in a healthy population with an ICC of 0.89 (95% CI: 0.79–0.95) (Gustavsson et al., 2006). The vertical jump was recorded using the Speed Light Sports Timing System (Swift Performance Equipment, PO Box 726, Lismore, NSW 2480, Australia). Participants were asked to stand on the jump mat with their uninjured leg only (single leg), with their hands behind their back, jump as high as possible off the mat, and land on the mat again on the same leg. The following criteria were required to deem a jump successful: no additional hop upon landing; no contact with the floor of either the opposite leg or either upper limb; balance must be maintained for two seconds upon landing, and the participants entire foot must land within the boundaries of the mat. The jump mat uses a sensor system to determine flight time from which jump height in centimetres was calculated. Once completed on the uninjured leg, the vertical jump was repeated on the injured leg.

*3.4.3 Strength Assessment*

Following the hop tests, participants then proceeded to the strength assessment of their quadriceps and hamstring muscles on the Biodex isokinetic dynamometer. Strength measures were secondary to the hamstring endurance measures for this study. Importantly though, assessment and calculation of hamstring peak torque enabled a percentage of this number to be established, upon which the initial target for the hamstring endurance test was determined (40% of hamstring peak torque). The uninjured leg was tested first. The isokinetic dynamometer has been shown to be a reliable and valid tool for measuring muscle strength of the quadriceps and hamstrings, with ICCs ranging from 0.79 to 0.99 (Feiring, Ellenbecker, & Derscheid, 1990; Montgomery, Douglass, & Deuster, 1989). Prior to testing, participants were set up according to the Biodex operating instructions, and the following parameters were recorded: Biodex position, chair height, chair position, chair depth, leg/arm length, seat incline. The lateral femoral condyles were lined up as accurately as possible by eye with the axis of rotation of the Biodex. Participants were placed in a semi-reclined position in the Biodex, with the seat upright reclined at 55°. This position was chosen as it replicated the functional position of running better than a fully raised chair upright which would place the hips in 90° of hip flexion. All straps were attached including two chest straps, a hip strap, a thigh strap, and an ankle strap. The knee range of motion was set from 10° to 90° for testing.

Quadriceps and hamstring strength were assessed in concentric mode at two different joint angular velocities: 120°/second and 180°/second. Participants warmed up on the isokinetic dynamometer performing a self-selected number of submaximal muscle efforts at each of 25%, 50% and 75% of MVC. Participants were given as much time as required to practice, to ensure they were ready for MVC test repetitions. For the latter, at 100% maximum effort, they were asked to work as hard and as fast as possible for five repetitions. Verbal encouragement was provided throughout the MVC test to ensure the participant gave maximum effort (McNair, 1996). Strength was assessed at a joint angular velocity of 120°/second firstly, followed by an assessment at 180°/second. The maximal torque recorded across the five repetitions of each angular velocity was utilised in the analyses.

The final strength test was a hamstring isometric strength test with the knee fixed at 90° knee flexion. In this position, the participant was asked to "pull their leg back" as hard as possible against the attachment, and hold for a 3–5 second period. Subjects were provided with one submaximal practice trial. Peak isometric hamstring strength was measured for three maximal effort trials, from which the highest torque value was recorded.

### *3.4.4 Hamstring Endurance Assessment*

For this test, the Biodex was set up in passive mode. The range of motion of the knee was set from 10° to 90° flexion. The joint angular velocity was set at 120°/second. The torque and angular displacement signals from the Biodex were linked to a second computer which displayed these signals so that the participants could monitor their output during the endurance test. Customised software (Superscope III, GW Instruments, 24 Spice St #301, Charlestown, MA 02129, USA) was developed for this purpose. Participants were given a warm-up to familiarise themselves with the test, and to ensure they had a full understanding of what was required during the test. A five-minute rest break was provided to each participant between the practice trial and the formal test to ensure that there were no fatigue effects on the hamstrings from the practice trial.

During the test, the knee joint moved through the above-mentioned standardised range of motion repetitively. In the extension phase of knee motion, the participants relaxed their muscles. However, during the flexion phase of the movement the participants activated their hamstrings, generating enough torque during flexion to reach and maintain a target level set on the screen in front of them. The participant was asked maintain the required level of torque throughout the full range of flexion only. The target level was initially set at 40% of the peak isokinetic hamstring torque (assessed as described in the previous section). The target remained at 40% of peak torque for the first two minutes of the endurance test. After two minutes, the target increased to 50% peak hamstring torque and remained at this level for the next two minutes. Thereafter, every two minutes the target level would increase by 10% until the participant was deemed to be fatigued. The participant was considered to be fatigued when they could not reach the target level on two consecutive repetitions. If the participant missed the target once, they were advised of this episode, and advised they needed to hit the target level on the next repetition. As the joint range of motion, joint angular velocity and torque target levels to be met were standardised, the number of repetitions that a participant could achieve was chosen as the dependant variable of interest. Additionally, it was thought that this variable could be utilised in clinical practice. Verbal encouragement was provided throughout the test to ensure maximum hamstring endurance was achieved (McNair, 1996). Participants rated their perceived exertion on the Borg scale (Borg, 1998) every minute during the test.

The reliability of this test was established in a pilot study. Thirteen individuals between the ages of 20 and 45 years completed the test on two occasions, 5–14 days apart. Six males and seven females participated in this phase of the study. The ICC calculated across the two occasions was 0.91 (95% CI: 0.72–0.97) for repetitions to fatigue, indicative of excellent reliability (Atkinson & Nevill, 1998).

### *3.4.5 Isometric Hamstring Strength Test and Hop Tests under Fatigued Conditions*

Immediately upon completion of the hamstring endurance protocol, the isometric hamstring strength test at 90° knee flexion was repeated once only. Thereafter, without delay, the participant performed two of the previously performed hops tests: the single hop for distance and triple hop for distance. The order of completion of these hop tests was randomised and completed within 2 minutes of finishing the submaximal hamstring endurance test. No practice trial was given and each test was completed only once.

**Figure 3.1 The participants' position of testing in the Biodex lab during the maximum effort strength test and submaximal endurance test.**

### 3.5 Data Analysis

Data analysis was carried out using the Statistical Package for Social Sciences (SPSS) software program version 2 (Chicago, IL, USA). Data were checked for errors and outliers using descriptive statistics, the boxplot, and Grubb's test. Data were also checked for normality using a combination of the Shapiro-Wilks test, skewness and kurtosis values, histogram plots, and the normal Q-Q plot.

An independent samples t-test was used to assess for any significant differences between the ACL group and the control group with regard to age, height and weight. Correlation analyses were used to identify any relationship between height or weight and strength, endurance or hop test measures.

For repetitions achieved, which was the primary outcome measure of hamstring endurance, a paired samples t-test was utilised to identify if there was a significant difference in hamstring endurance across the involved leg and the uninvolved leg of the ACL participants. An independent samples t-test was used to investigate the difference in hamstring endurance (repetitions achieved) between the uninjured leg of the ACL group and the control group.

The Pearson product-moment correlation coefficient and Spearman's Rho correlation coefficient were used to investigate the relationship between hamstring endurance and both perceived knee function and performance-based knee function.

A two-factor repeated measures ANOVA was used to investigate the single and triple hop performance across baseline and fatigued conditions and across legs in the ACL-reconstructed cohort. A separate mixed (between and within) factorial ANOVA was undertaken for comparison across the uninvolved limb of the ACL cohort and the control group limb. Contrasts (t-tests) were planned across legs and fatigue depending upon main effect/interactions that might be observed. For all of the above tests, an alpha level of 0.05 was set as the level of significance.

# Chapter 4 Results

## 4.1 Introduction

This chapter is divided into four main sections. Section 4.2 outlines the demographic details of the participants who took part in the study. Section 4.3 is related to the first research question and provides the results from the hamstring endurance test across legs. Section 4.4 is related to the second research question and presents the findings regarding the relationship between knee function measures and hamstring endurance. Finally, section 4.5 addresses the third research question concerning performance-based measures (hop tests) under fatigue.

## 4.2 Participant Details

Forty-eight participants were recruited in total. Of these, 24 participants were recruited into the injured group who had undergone ACL reconstruction surgery 9–13 months previously. [Note: two additional participants were included at the end of recruitment who met all other inclusion criteria except for time since surgery, and therefore were included in the study.] Twenty-four age-, gender- and activity-matched healthy individuals were recruited into the control group.

In both the ACL-injured group and the control group there were 14 males and 10 females. The ACL group had a mean age of 33 years (+/- 8), ranging from 21 to 51 years. The participants in this group had a mean height and weight of 172.0cm (+/- 7.68) and 75.71kg (+/- 14.89) respectively, and time since surgery was 10.54 months (+/- 1.35). Of the 24 ACL-injured participants, nine had a semitendinosus graft and 15 had a semitendinosus and gracilis graft. The control group had a mean age of 33 years (+/- 8), ranging from 21 to 52 years. They had a mean height and weight of 171.2cm (+/- 8.72) and 72.42kg (+/- 14.88) respectively. There were no significant differences ($p > 0.05$) between the ACL group and the control group in age, height and weight. Fifty-eight percent of participants in the ACL group were involved in competitive recreational sport at the time of injury. The remaining 42% of the ACL group were involved in social sport at the time of injury. At the time of testing, 33% of participants had been cleared for return to their pre-injury sport by either their orthopaedic surgeon or their physiotherapist. Despite this, only 8% of participants had returned to their pre-injury level of sport at the

**Table 4.1**

***Demographic Data for Participants in Phase 2 of the Study***

| | ACL-Injured Group | Control Group |
|---|---|---|
| ***Number of Participants*** | 24 | 24 |
| - Male | 14 | 14 |
| - Female | 10 | 10 |
| ***Ethnicity*** | | |
| - NZ Pākehā | 7 | 8 |
| - NZ Māori | 1 | 2 |
| - Pacific | 1 | - |
| - Asian | 3 | - |
| - Other European | 9 | 13 |
| - Middle Eastern | 2 | - |
| - Indian | 1 | - |
| - NZ Pākehā/Filipino | - | 1 |
| ***Age*** | | |
| - Mean (SD) | 33 (8) | 33 (8) |
| - Range | 21-51 | 21-52 |
| ***Height (cm)*** | | |
| - Mean (SD) | 172.04 (7.68) | 171.15 (8.72) |
| ***Weight (kg)*** | | |
| - Mean (SD) | 75.71 (14.89) | 72.42 (14.88) |
| ***Time Since Surgery (months)*** | | |
| - Mean (SD) | 10.54 (1.35) | - |
| - Range | 9-13 | - |
| ***Graft*** | | |
| - Semitendinosus | 9/24 | - |
| - Semitendinosus + Gracilis | 15/24 | - |
| ***Meniscal Surgery*** | | - |
| - Menisectomy | 6/24 | - |
| - Meniscal Repair | 3/24 | - |
| - Meniscal Repair + Menisectomy | 3/24 | - |
| ***Return to Pre-Injury Level of Sport (%)*** | | |
| - Yes | 2/24 (8.3%) | - |
| - No, decreased | 20/24 (83.3%) | - |
| - No, stopped sport due to ACL injury | 2/24 (8.3%) | - |
| - Stopped sport (not due to injury) | 0/24 (0%) | |
| - Received formal clearance for return to sport | 8/24 (33%) | |

time of testing, and 83% reported a decreased level of sporting activity. The participants who reported a decreased level of sporting activity included those who were still engaged in rehabilitation with the aim of returning to sport, but who had yet to return to any training or game time for their pre-injury sport, those who had returned to training sessions only, and those who had returned to a combination of training and limited game time for their pre-injury sport. All participant demographic details are displayed in Table 4.1.

For the KOOS, participants scored between 61% and 95% across all five sections with a mean total score of 86%. For the LLTQ, participants scored a mean value of 39/40 for the Activities of Daily Living section and 30/40 for the Recreation section. The mean score for the Psychological Readiness to Return to Sport Questionnaire was 41. See Table 4.2 for results.

**Table 4.2**

***Raw Data for Perceived Knee Function from Subjective Questionnaires for the ACL Group***

| | Mean (SD) |
|---|---|
| **KOOS (%)** | |
| - Pain | 89.2 (9.8) |
| - Symptoms | 79.6 (12.7) |
| - Activities of Daily Living | 94.5 (8.7) |
| - Sport | 77.7 (15.2) |
| - Quality of Life | 61.2 (15.8) |
| - Total | 85.7 (8.6) |
| **Lower-Limb Task Questionnaire (LLTQ)** | |
| - Activities of Daily Living (/40) | 38.6 (2.4) |
| - Recreation (/40) | 30.4 (4.8) |
| **Psychological Readiness to Return to Sport (/60)** | 40.9 (12.6) |

Table 4.3 displays the raw data for isokinetic strength measures across groups. Deficits of 14–20% were observed across the injured and uninjured legs for quadriceps strength, and 11–14% deficits were observed across legs for hamstring strength. There was a significant difference ($p < 0.05$) between the injured and uninjured leg across all measures of quadriceps and hamstring strength in the ACL group. There were no significant differences ($p > 0.05$) observed for quadriceps or hamstring strength between the uninjured leg and the healthy control leg.

**Table 4.3**

***Baseline Data for Isokinetic Muscle Strength Testing (Quadriceps and Hamstring Strength)***

| | **Injured (Nm)** <br> **Mean (SD)** | **Uninjured (Nm)** <br> **Mean (SD)** | **Limb Symmetry Index (%) #** <br> **Mean (SD)** | **Control (Nm)** <br> **Mean (SD)** |
|---|---|---|---|---|
| **Quadriceps 120°/second** | 130.6 (41.7) | 162.0 * (45.3) | 80.1 (12.4) | 151.5 (40.3) |
| **Quadriceps 180°/second** | 116.8 (34.2) | 136.3 * (38.8) | 85.9 (10.1) | 129.4 (38.0) |
| **Hamstrings 120°/second** | 74.4 (23.2) | 86.3 * (23.8) | 86.1 (12.2) | 87.3 (28.7) |
| **Hamstrings 180°/second** | 75.3 (20.3) | 85.8 * (24.6) | 88.8 (12.4) | 85.6 (29.8) |

*Note.* * $p < 0.05$ between the injured and uninjured legs; # Limb Symmetry Index: the ratio of the involved to uninvolved limbs multiplied by 100.

When investigating the association between height and jump distance, a significant positive relationship was found between height and all five hop tests across all legs. R coefficients ranged from 0.41 to 0.69. Hence, jump distance as a proportion of height was calculated across all hop tests except the side hop (where raw scores were used), and was utilised for all further analyses. Table 4.4 displays the mean values for these hop tests as a proportion of height (see Appendix J for raw values). Deficits up to 11% were observed across the injured and uninjured legs of the ACL group. There was a significant difference observed between the injured and uninjured leg for the single hop for distance, triple hop for distance, crossover hop for distance and side hop. There was no significant difference across legs for the vertical jump. There were no significant differences observed between the uninjured leg of the ACL group and the control leg for any of the hop tests.

**Table 4.4**

***Baseline Hop Test Scores as a Proportion of Height***

| | Injured<br>Mean (SD) | Uninjured<br>Mean (SD) | Limb Symmetry Index (%) #<br>Mean (SD) | Control<br>Mean (SD) |
|---|---|---|---|---|
| **Single Hop for Distance** | 0.69 (0.18) | 0.73 * (0.16) | 93.6 (8.9) | 0.76 (0.14) |
| **Triple Hop for Distance** | 2.20 (0.52) | 2.29 * (0.45) | 95.8 (7.7) | 2.5 (0.46) |
| **Crossover Hop for Distance** | 1.94 (0.52) | 2.02 * (0.41) | 94.9 (10.6) | 2.2 (0.46) |
| **Vertical Jump** | 0.09 (0.04) | 0.09 (0.03) | 102.9 (39.2) | 0.11 (0.05) |
| **Side Hop (Repetitions) ^** | 22.9 (11.0) | 25.2 * (9.1) | 88.7 (18.8) | 31.2 (13.0) |

*Note.* * $p < 0.05$ between the injured and uninjured legs; # Limb Symmetry Index: the ratio of the involved to uninvolved limbs multiplied by 100; ^ side hop reported as raw value in repetitions.

## 4.3 Hamstring Endurance

There was a statistically significant difference ($p < 0.05$) in hamstring endurance across legs with a mean number of repetitions to fatigue in the injured leg of 111 repetitions (SD 49) and the uninjured leg of 136 repetitions (SD 67), amounting to an 18% deficit. Cohen's d effect size was 0.43.

Using an independent samples t-test, there was no significant difference in hamstring endurance between the uninjured leg (mean = 136 repetitions, SD 67) and the healthy control group (mean = 124 repetitions, SD 50). Cohen's d effect size was 0.2 (Figure 4.1).

The mean LSI for hamstring endurance of the ACL group was 90.1% (SD 31.5).

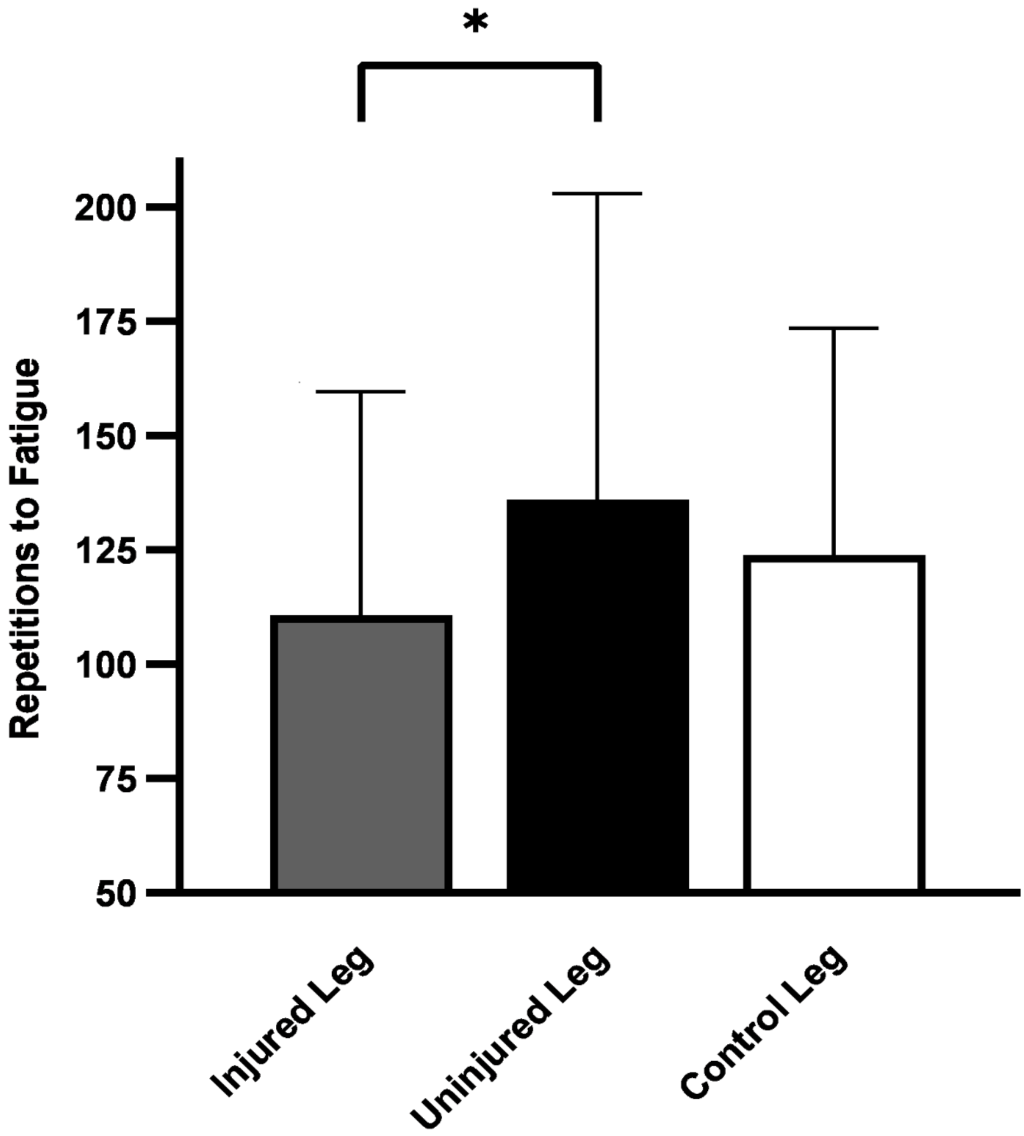


**Figure 4.1 Hamstring endurance (repetitions to fatigue) of the injured leg, uninjured leg and healthy control leg. Data are means and standard deviations. * indicates $p < 0.05$ across involved and uninvolved limbs.**

### 4.4 Relationship between Hamstring Endurance and Knee Function

No significant relationships were observed for the number of repetitions performed on the ACL-injured leg during the hamstring fatigue test and the following performance-based variables on the injured leg only: single hop for distance post-fatigue and triple hop for distance post-fatigue. R coefficients ranged from -0.13 to -0.10.

No significant relationships were observed for the number of repetitions performed on the ACL-injured leg during the hamstring fatigue test and the following self-reported variables: the KOOS Sports and Recreation, the LLTQ Recreation and the Psychological Readiness to Return to Sport (IPPRS). R coefficients ranged from -0.035 to 0.10.

No significant relationships were observed for the LSI for the number of repetitions performed in the hamstring fatigue test and the following performance-based variables: LSI for single hop for distance post-fatigue and LSI for triple hop for distance post-fatigue. R coefficients ranged from -0.23 to -0.04.

No significant relationships were observed for the LSI for the number of repetitions performed in the hamstring fatigue test and the following self-reported variables: KOOS Sports, LLTQ Recreation and IPPRS. R coefficients ranged from 0.12 to 0.21.

## 4.5 Knee Function under Fatigue

### *4.5.1 Evidence of Fatigue*

In respect of isometric hamstring strength prior to and immediately after fatigue, the findings showed that isometric strength after the fatigue test was 39%, 46% and 44% lower in the injured, uninjured and control legs respectively. The mean Borg score for perceived exertion at the completion of the hamstring fatigue test was 19 for all three groups. Absolute values for the isometric hamstring test can be seen in Table 4.5.

**Table 4.5**

***Absolute Values for Isometric Hamstring Strength at 90° Knee Flexion Pre and Post Hamstring Fatigue***

| | **Pre-Fatigue (Nm) Mean (SD)** | **Post-Fatigue (Nm) Mean (SD)** | **Change/Reduction (%)** |
|---|---|---|---|
| **Injured Leg** | 40.8 (18.3) | 24.7 (13.8) | 39% |
| **Uninjured Leg** | 62.7 (22.0) | 34.0 (13.8) | 46% |
| **Control Leg** | 56.5 (17.6) | 31.8 (9.3) | 44% |

*4.5.2 Single Hop for Distance*

For the single hop for distance under both pre-fatigue and post-fatigue conditions in the ACL group, no significant interaction effect ($p > 0.05$) was found across legs and time periods (effect size = 0.13). There was a significant main effect ($p < 0.05$) for both fatigue (effect size = 0.53) and legs (effect size = 0.49). As shown in Figure 4.2, the results indicate that the single hop for distance in the ACL-injured leg was significantly less than the uninjured leg both pre and post hamstring fatigue.

For the comparison of the uninvolved limb of the ACL-reconstructed group and the control group leg, a mixed between-within subjects analysis of variance showed no significant interaction effect ($p > 0.05$) across legs and time periods. However, there was a significant main effect for fatigue (effect size = 0.41). As shown in Figure 4.2, the results indicate that there was a significant reduction in single hop for distance scores for both legs post hamstring fatigue. The main effect for legs was not significant (effect size = 0.014) (see Figure 4.2).

*4.5.3 Triple Hop for Distance*

For the triple hop for distance under both pre-fatigue and post-fatigue conditions in the ACL group, no significant interaction effect was found across legs and time periods ($p > 0.05$), (effect size = 0.10). There was a significant main effect ($p < 0.05$) for both fatigue (effect size = 0.76), and legs (effect size = 0.35). As shown in Figure 4.3, the results indicate that the triple hop for distance was significantly less in the ACL-injured leg compared to the uninjured leg both pre and post hamstring fatigue.

Finally, a mixed between-within subjects analysis of variance assessing the ACL-uninjured leg and the healthy control leg pre and post hamstring fatigue showed a significant interaction effect ($p = 0.049$) across legs and fatigue; however, the effect size was small (effect size = 0.08). In light of the interaction effect, subsequent contrast tests showed that there was a significant difference pre- and post-fatigue in both legs, and a trend for the uninvolved limb to have a notably lower jump distance pre-fatigue than the control limb, yet post-fatigue the difference in their hop distances was reduced. Tests of between subjects effects showed no significant difference across uninjured and control limbs.

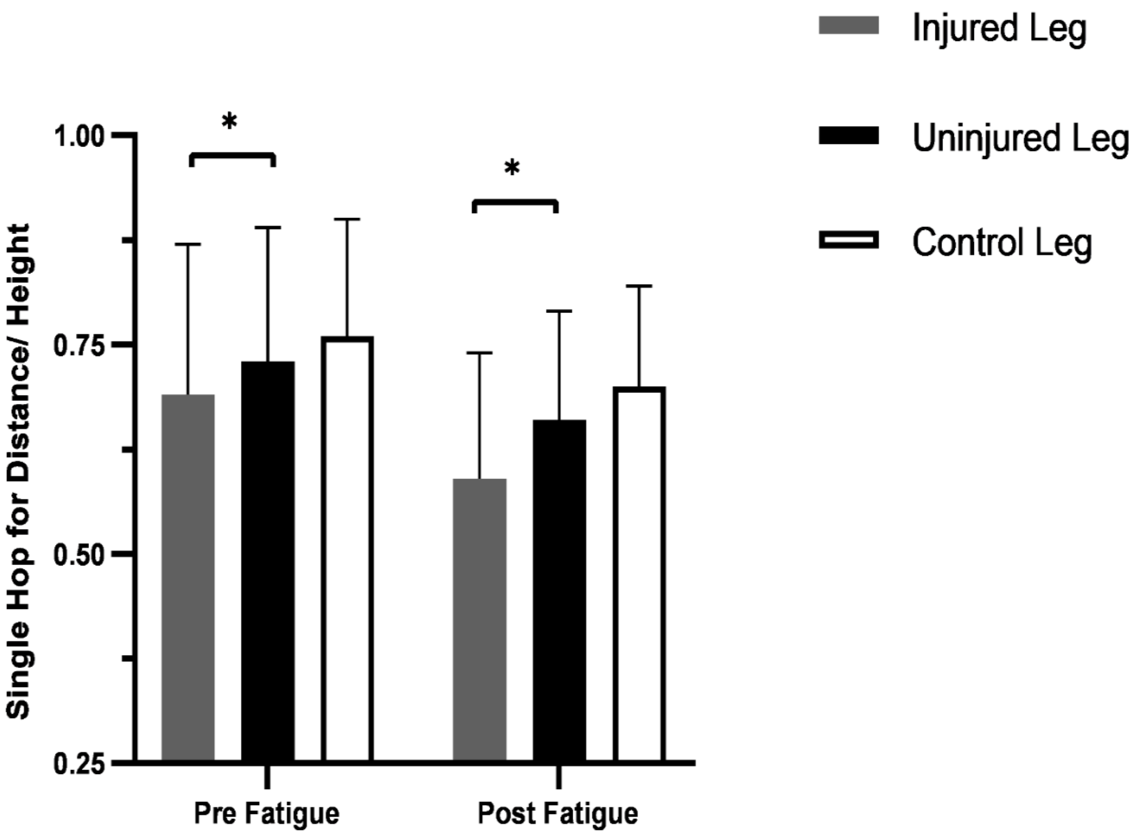


**Figure 4.2 Single hop for distance pre and post hamstring fatigue for the injured, uninjured and healthy control legs. * indicates p < 0.05 across involved and uninvolved limbs. Note: there was also a significant main effect for fatigue across all legs. Data are means and standard deviations.**

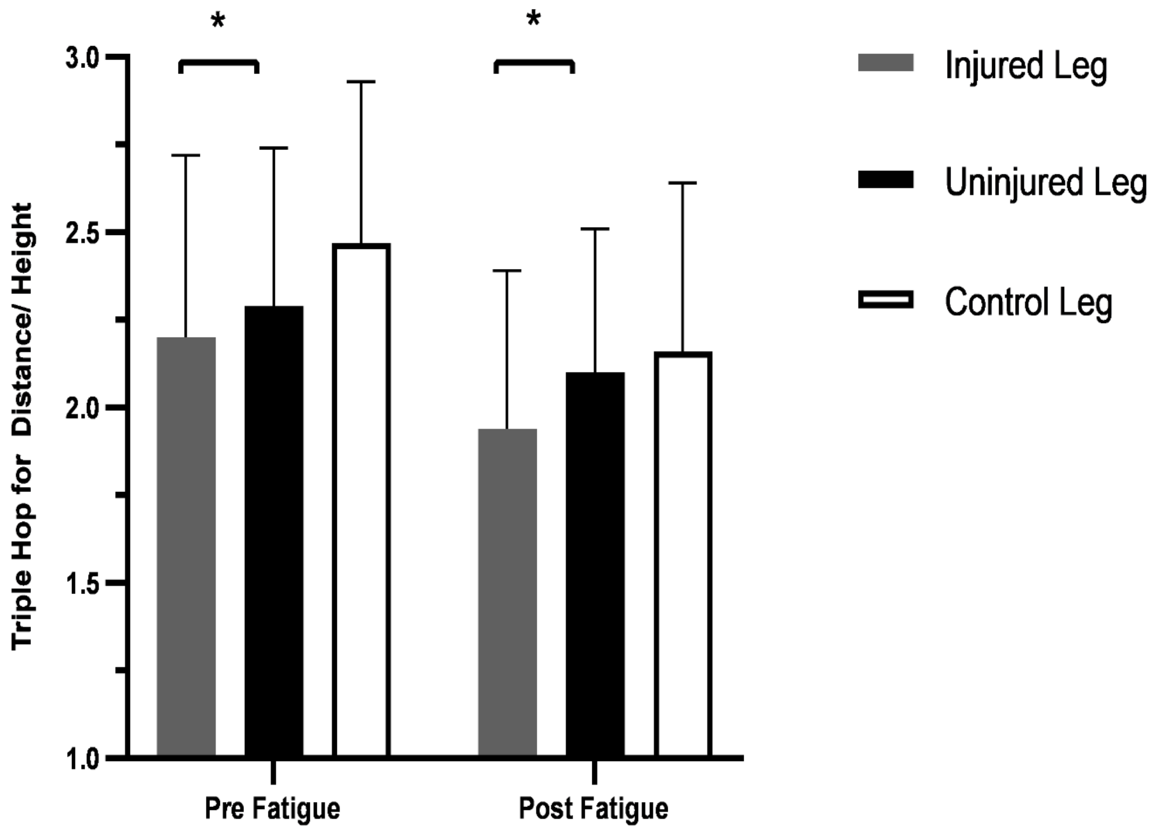


**Figure 4.3 Triple hop for distance pre and post hamstring fatigue for the injured, uninjured and healthy control legs. * indicates $p < 0.05$ across involved and uninvolved limbs. Note: a small but significant interaction effect was observed across the uninjured and control legs. Data are means and standard deviations.**

# Chapter 5 Discussion

## 5.1 Introduction

The body of research relating to hamstring endurance following an ACL reconstruction is limited, despite the importance of muscle endurance capability for many sport and recreational activities. The primary aim of the current study was to investigate hamstring endurance in this group. The main finding of this study demonstrated a significant difference in hamstring endurance between the ACL injured leg and ACL uninjured leg 9-12 months post ACL reconstruction with a hamstring graft, with an 18% deficit noted on the injured leg when measured by repetitions to fatigue. There was no significant difference in hamstring endurance between the uninjured leg and a healthy control group. A secondary finding was that there was no significant relationship demonstrated between hamstring endurance of the injured leg and any of the measures of knee function utilised, including both performance-based measures and self-reported questionnaires. The final aim of this study was to investigate hop performance of the injured leg under hamstring fatigue, and compare this to the uninjured leg and leg of a healthy control group. There was a significant difference in hop performance between the injured and uninjured legs only, for both the single hop for distance and the triple hop for distance, both pre and post-fatigue. There was an 11% deficit and a 7% deficit respectively between legs post-fatigue. These key findings are discussed in more detail below.

## 5.2 Analysis of Study Participants

While the mean age of the participants was 33 years and was similar to that in the study by D. Lee et al. (2015) which investigated hamstring muscle endurance after an ACL reconstruction with a hamstring graft, all other studies which have investigated hamstring endurance and also hop performance involved a younger cohort of participants, with a mean age ranging from 20 to 28 years (Augustsson et al., 2004; de Fontenay et al., 2015; Ebert et al., 2018; Gokeler, Welling, Benjaminse, et al., 2017; Gustavsson et al., 2006; Thomeé et al., 2012; Tow et al., 2005; Vairo, 2014; Vairo et al., 2008). As mentioned in the methods section, the inclusion criteria was greater than 20 years due to ethical considerations in a younger cohort (see page 62). The mean height and weight of the ACL and control group in the current study were similar to previous research in this area (Bie Larsen et al., 2015; D. Lee et al., 2015; Thomeé et al., 2012). When analysing all participants, 58% of participants were involved in competitive recreational sports at the time of injury. The remaining 42% were involved in social sports. Competitive recreational activity levels involved regular training sessions for their chosen sport as well as competitive games/events. When comparing this cohort to the literature which investigates both hamstring endurance capability and hop performance in an ACL-reconstructed population, comparison is difficult, as a number of researchers (Bie Larsen et al., 2015; D. Lee et al., 2015) do not mention the pre-injury activity level of participants. When analysing those studies that do report on pre-injury activity level (Augustsson et al., 2004; Vairo, 2014; Vairo et al., 2008), a number of researchers are vague in their description and list 'recreational athletes' as an inclusion criterion without any other detail regarding type, frequency or intensity of the activity. The Noyes Sports Activity Scale has also been utilised previously in studies by Ebert et al. (2018) and Gokeler, Welling, Benjaminse, et al. (2017) to determine pre-injury activity level. These authors included participants who were involved in Level I and Level II activities according to the Noyes Scale which is comparable to the cohort in the current study.

Concerning the return to sport after reconstruction, 8% of participants in the current study had returned to their pre-injury level of sporting activity at a mean of 10.5 months post-surgery, 8% had stopped their pre-injury sporting activity due to their ACL injury, and 83% of participants were performing with decreased participation in their pre-injury sport. Decreased participation included participants who were engaged in ongoing rehabilitation with the aim of returning to their sport, and/or had returned to training sessions only, or had returned to a combination of training and limited game time. These results are similar to those identified by Bie Larsen and colleagues (2015), where 13% of participants had returned fully to their pre-injury sport. However, these authors reported that a much lower number had returned to sport at a decreased level (13%). In contrast, Grindem and colleagues (2016), reported that 89% of participants had returned to their pre-injury level of sport 8 months post-surgery, which is vastly different to the results observed in the current study. One reason for the large discrepancy across studies is likely the nature of the rehabilitation completed. For instance, all participants in the study by Grindem and colleagues (2016) completed a comprehensive supervised and standardised rehabilitation programme both pre-operatively and post-operatively. Rehabilitation sessions took place a minimum of two and a maximum of four times per week, and two sessions per week were supervised. This level of supervision during rehabilitation may have produced a much greater success rate for returning to pre-injury activity levels. Despite not having information regarding the exact nature of the rehabilitation undertaken for the current cohort, either pre- or post-operatively, the rehabilitation was not standardised across the cohort, and it is unlikely the same level of supervision was provided given the constraints on funding for post-surgical rehabilitation within the New Zealand health system.

Regarding perceived symptoms and function, using the KOOS Scale, the mean scores for each of the five subscales in the current study were as follows: pain, 89%; symptoms, 80%; activities of daily living, 95%; sports and recreational activities, 78% and quality of life, 61%. These scores were in keeping with scores reported elsewhere in the literature for perceived function at 12 months post-surgery (Antosh et al., 2018; Azus et al., 2018; Beischer et al., 2018; Bodkin et al., 2017; Samuelsson et al., 2017). The mean score on the LLTQ in the current study was 39/40 for the activities of daily living section and 30/40 for the recreation section. The results from both questionnaires, the KOOS and the LLTQ, display high levels of perceived function for activities of daily living across both scales, and greater deficits in perceived function for the sports and recreation sections. The mean value on the Psychological Readiness to Return to Sport questionnaire was 41/60 which indicates moderate confidence in returning to sport (Slagers, Van den Akker-Scheek, Geertzen, Zwerver, & Reininga, 2019). These results are in line with previous literature (Hart, Culvenor, Guermazi, & Crossley, 2020; Lefevre et al., 2017; Meierbachtol, Yungtum, Paur, Bottoms, & Chmielewski, 2018; Welling et al., 2018), which has used the Anterior Cruciate Ligament – Return to Sport Index (ACL-RSI) and reported a mean score of 53%–73% at 8–12 months post-reconstruction, where a score of 100% indicates full confidence to return to sport

In respect of quadriceps muscle strength, mean deficits of 14%–20% were observed in the current cohort. Whilst the deficits demonstrated at 180°/second are similar to those reported by Czaplicki and colleagues (2015), those observed at 120°/second are much higher than the 11% deficit that Czaplicki and colleagues observed at a knee joint velocity of 60°/second. In the current study, no significant differences in quadriceps strength were observed between the uninjured leg and the healthy control leg, which for the most part is supported across the literature (Bie Larsen et al., 2015; Mirkov et al., 2017; Mohammadi et al., 2013; Petschnig et al., 1998). Contradicting these results, however, Bie Larsen and colleagues (2015) reported a significant difference between the uninjured leg and a healthy control leg for quadriceps peak torque at 180°/second, with higher values in the healthy control leg at 12 months post-surgery.

Regarding hamstring strength, the results of our study demonstrated a mean deficit of 11–14%, which is similar to Ebert et al. (2018) who reported a deficit of 9% at a joint angular velocity of 90°/second. In contrast, Czaplicki et al. (2015) found no significant difference in hamstring torque between legs at 12 months post-surgery. In our study there were no significant differences observed for hamstring strength between the uninjured leg and the healthy control leg, which is in agreement with some researchers (Mirkov et al., 2017; Mohammadi et al., 2013) but not all (Bie Larsen et al., 2015; Hiemstra et al., 2007)

In the current study, pre-fatigue, the hop performance of the injured leg was significantly lower compared to the uninjured leg, ranging from 4% to 11%. These results were in agreement with other literature (Currie et al., 2018; D. Lee, Yang, Cho, Lee, & Kim, 2018; Niemeyer et al., 2019; Thomeé et al., 2012; Zwolski, Schmitt, Thomas, Hewett, & Paterno, 2016) which has demonstrated a 5–9% deficit between limbs for the single hop for distance, a 6–7% deficit for the triple hop for distance, a 5–7% deficit for the crossover hop for distance, and a 13% deficit for the side hop, at a mean follow up of 9–12 months post-surgery with participants predominantly having had a hamstring graft. In contrast, Bie Larsen and colleagues (2015) found a larger deficit of 18% for the single hop for distance at a mean follow up of 11 months post-surgery for participants with either a BPTB or hamstring graft, and Niemeyer and colleagues (2019) found a 13% deficit in the single hop for distance between legs 9–19 months post-reconstruction for participants with a hamstring graft only. In contrast to the current study, where there was no difference, D. Lee et al. (2018) and Myer et al. (2012) reported an 11% deficit in vertical jump height between the ACL-injured and uninjured legs 9 months after an ACL reconstruction. Like the results pertaining to strength, it is likely such differences in hop performance reflect participants' participation levels in sport, as well as the nature of their rehabilitation.

In summary, the demographic data outlined above reflects the relative homogeneity of the current group of participants compared to cohorts in previous research. Participants in the current study had a mean age of 33 years, were a mean of 10.5 months post ACL reconstruction with a hamstring graft and included both competitive and recreational athletes. Whilst 33% of participants had received formal clearance to return to their pre-injury level of sport, only 8% had achieved a full return to pre-injury activity levels.

## 5.3 Analysis of Hamstring Endurance

Firstly, in regard to the fatigue protocol, research to date investigating hamstring endurance has been undertaken with isokinetic dynamometers and has involved maximal effort muscle testing (D. Lee et al., 2015; Tow et al., 2005; Vairo, 2014; Vairo et al., 2008). In contrast, our protocol involved progressive force requirements for the hamstring muscles commencing at 40% maximum voluntary effort. As such, the protocol elicited prolonged activity from muscle fibres activated at submaximal levels of force potential and hence involved increased aerobic metabolic processes within the muscle compared to that occurring at maximal effort repetitively (Fitts, 1994). However, as the test proceeded, increased effort was required from participants, and therefore it is likely that an increase in metabolites in the muscle (as described in section 2.5) had a progressively greater impact on fatigue as the test progressed. Additionally, it is likely that central activation patterns during submaximal exercise are different to those observed in repetitive maximal effort scenarios, and perhaps had a more dominant role during this study (Finn et al., 2018; Taylor & Gandevia, 2008). A progressive increase in the reported Borg score was observed in the current study, with the mean score reported at the time of task failure being 19 across all groups. This is similar to other studies for a submaximal fatiguing task (Finn et al., 2018; Hunter, McNeil, Butler, Gandevia, & Taylor, 2016) and the authors of these studies suggest that the progressive increase in the Borg score shows evidence for increased voluntary descending drive to maintain motoneuron excitability. Central fatigue occurring at the level of the motoneurons is often thought to be due to changes in their intrinsic properties resulting in reduced excitability (Finn et al., 2018). Additionally, peripheral inputs (e.g., type III-IV afferents) can influence the ability of the motor unit to fire effectively (Cairns et al., 2017). Overall, the ability of descending drive to stimulate the motoneurons is reduced, adding to the aforementioned metabolic impairments that occur within the muscle and ultimately leading to reduced force potential. These differences in the mechanisms of muscle fatigue during submaximal and maximal effort activity highlights the importance of understanding hamstring endurance capability during a submaximal effort task which, it could be argued, better replicates most sport and recreational activities.

A significant difference was found between the injured leg and uninjured leg, with a mean deficit of 18% in hamstring endurance in the involved limb. A similar deficit (16%) was reported by D. Lee and colleagues (2015), who used a maximal effort endurance task. There are no other studies to date which have investigated the endurance of the hamstring muscles 9–12 months post-surgery. Given the extensive literature reporting muscle strength deficits in this population post-surgery, and the small number of studies investigating muscle endurance performance, it is likely that the physiotherapists involved in the rehabilitation of the current cohort placed more emphasis upon muscle strength recovery as compared to muscle endurance.

Within the ACL literature, there is generally concern expressed when deficits are greater than 10% for strength and functional performance hop tests. Hence, the observed 18% deficit in hamstring endurance between legs is notable. From a return-to-sport perspective, if endurance is added to the elements of the European Board of

Sports Rehabilitation (Thomeé et al., 2011), and the same passing criteria as for strength are implemented for a pivoting/contact/competitive sport (i.e., 100% LSI), only 25% of the current cohort would pass. If one reduced the criteria requirement to 90% LSI (i.e., 10% deficit), then 63% would pass. In light of these points, and the important role the hamstring muscles play in reducing stress on the ACL graft, the inclusion of hamstring muscle endurance within the rehabilitation programme and the return-to-sport assessment is worthy of further attention.

A number of researchers (T. Anderson & Kearney, 1982; Campos et al., 2002; Shigaki et al., 2018; Stone & Coulter, 1994) have highlighted programmes that can improve muscle endurance. The general focus of such programmes is on utilising low to moderate resistance coupled with high repetitions (American College of Sports Medicine, 2009). This has typically involved trainings loads of one to three sets of 20–40 repetitions maximum. A training frequency of two to three sessions per week has been recommended (American College of Sports Medicine, 2009). Findings show that such training parameters can lead to 20% to 137% improvements in muscle endurance over 9–10 weeks (T. Anderson & Kearney, 1982; Campos et al., 2002; Shigaki et al., 2018; Stone & Coulter, 1994).

## 5.4 Analysis of Relationship between Hamstring Endurance and Function

In the current study, a novel finding was that there was no significant relationship demonstrated between absolute hamstring endurance or hamstring endurance LSI of the ACL-injured group and any of the self-reported or functional performance-based measures. Bodkin and colleagues (2017) reported a strong and significant relationship between hamstring endurance and the KOOS Quality of Life subscale only ($r = 0.717$) in a hamstring graft group at 17 months post-surgery. However, the endurance testing protocol in this study involved only eight maximal effort repetitions, in comparison to submaximal effort repetitions to fatigue in the current study. If one considers the different mechanisms of muscle fatigue for maximal and submaximal exercise, as previously outlined, a direct comparison of these results is difficult. In addition, the mean follow-up time was much less in the current study (11 months vs 17 months) and it could be that the additional time is needed for the participants in the current study to be exposed to sporting tasks and activities that would be similar to their pre-injury levels of participation. Such additional training and experience may provide them with a better perception of their abilities.

An alternative perspective might be that the level of hamstring muscle activity observed in critical situations where an injury to the ACL may occur requires immediate high hamstring activation/force, and hence maximal force or rate of force development might be more important than endurance capability. Relatedly, the hop tests performed are undertaken with the goal of achieving maximal distance and hence require maximal effort from muscle groups involved. Research in non-injured samples supports this theory (Hamilton et al., 2008), and has shown a moderate correlation ($r = 0.75$) between distance jumped and hamstring strength. Additionally, research in an ACL-reconstructed population (J. Kim et al., 2011; Ko et al., 2012) has shown a moderate and significant negative correlation between the hamstring strength deficit measured at 60°/second and the single hop for distance in a hamstring graft group, at mean follow-up times of 12 months ($r = -0.312$), 24 months ($r = -0.354$) and 32 months ($r = -0.43$) post-surgery. Furthermore, a significant correlation has also been demonstrated (Bodkin et al., 2017; Harput et al., 2018) between hamstring strength and self-reported function. However, a number of researchers (J. Kim et al., 2011; Lautamies et al., 2008) report no relationship between these variables.

Of further note, it is logical to think that a number of variables contribute to perceived function and hop performance, and their relative contribution to performance in a maximal effort hop-like task probably differs across individuals. Hop performance is influenced by more than hamstring strength or endurance alone, and the quadriceps and hip extensor muscles also play an important role in optimising hop performance. It would also seem reasonable to consider that perceived function is based on more than just the specificity associated with muscle function, and is influenced by fear of re-injury, and confidence in the ability of one’s knee to perform various tasks (Mahood et al., 2020).

## 5.5 Analysis of Hop Performance under Hamstring Fatigue

The results of the current study are the first to describe hop performance following hamstring muscle fatigue in a group of participants after an ACL reconstruction with a hamstring tendon graft. The 39%, 46% and 44% decline in isometric hamstring strength for the injured, uninjured and control legs respectively, after the hamstring endurance protocol, provided evidence of fatigue. In addition, the progressive change in Borg values as the test progressed, and the final value reported upon completion of the fatigue test of 19 across control and ACL groups, is indicative of maximal effort (Thompson, Gordon, & Pescatello, 2010).

Single and triple hop distances were decreased on each leg following fatigue, with reductions that varied between 8% and 14%. There was a significant difference between the injured and uninjured legs for the distance jumped on both the single hop for distance and triple hop for distance post hamstring fatigue. When taking the LSI of the ACL group into consideration, the single hop for distance had an LSI of 94% pre-fatigue, which decreased to 89% post-fatigue, while the triple hop had an LSI of 96% pre-fatigue which dropped to 93% post-fatigue. These are relatively small changes. Research on hop performance under fatigued conditions is limited across the literature with only two studies, one in an ACL-reconstructed population (Augustsson et al., 2004) and one in a healthy population (Augustsson et al., 2006). In both studies the quadriceps were fatigued. Nevertheless, Augustsson and colleagues (2004) reported an LSI of 97% pre-fatigue compared to an 89% LSI post-fatigue on the single hop for distance in a group 11 months after an ACL reconstruction.

In the current study, 33% of participants had received formal clearance by their surgeon or physiotherapist to return to their pre-injury sport by 10.5 months post-surgery, yet only 8% reported a full return to their pre-injury sport. While there is no internationally accepted return-to-sport test battery following an ACL reconstruction, some suggestions have been made (Kyritsis et al., 2016; Thomeé et al., 2011). The European Board of Sports Rehabilitation (Thomeé et al., 2011) provides guidelines regarding the return to sport that are based on the type of sport an individual is returning to play. If an individual is returning to a pivoting, contact or competitive sport, they should demonstrate a 90% LSI for two maximum hop tests (e.g., single hop for distance and vertical jump) as well as one multiple hop test (e.g., side hop, triple hop for distance, or crossover hop for distance). If returning to a non-pivoting, non-contact and recreational sport, individuals should demonstrate a 90% LSI on one maximum or one multiple hop test. Relating these criteria to the current study, 50% of participants would have passed the hop test component of the test battery (pre-fatigue).

If the hop test scores under fatigued conditions from the current study are utilised as part of the return-to-sport criteria outlined by Thomeé and colleagues (2011), only 33% of participants would pass the hop test criteria under fatigue. Furthermore, in the current study, of the participants who achieved an LSI of greater than 90% for the pre-fatigue single hop for distance and triple hop for distance, 29% (single hop) and 21% (triple hop) had an LSI of less than 90% under fatigued conditions. These data provide a strong argument for including testing under fatigued conditions within a return-to-sport testing battery. As outlined previously, there is a relationship between hamstring strength and how far an individual can jump. Therefore, if hamstring fatigue is present, jump distance is likely to be affected. More importantly, one would suspect that the ability of the hamstrings to reduce the load on the reconstructed ACL during such activities would be compromised by fatigue.

Hop distance is not the only parameter that can change under fatigued conditions in an ACL-reconstructed group. Several studies (Frank, Gilsdorf, Goerger, Prentice, & Padua, 2014; Kuenze et al., 2014; Lessi, Silva, & Serrão, 2018; Webster, Santamaria, McClelland, & Feller, 2012) have investigated kinematic and kinetic variables in an ACL-reconstructed population under fatigued conditions between 16 and 36 months post-surgery. The findings across these studies are conflicting, with a number of researchers finding no significant differences between groups for the selected variables (Frank et al., 2014; Kuenze et al., 2014). However, a significant decrease in peak hip flexion angle and ankle dorsiflexion angle, and an increase in hip and knee abduction angle and knee internal rotation angle has been demonstrated under fatigue when comparing the ACL reconstructed limb with a healthy control limb during a single leg drop landing task (Webster et al., 2012) More recently, Lessi and colleagues (2018) reported a greater knee abduction angle in females following an ACL reconstruction during a similar task. These changes in biomechanics during a landing task may increase the load on the knee joint and graft, and increase one’s risk of re-injury. This is particularly true of the increases noted in knee abduction angle, which have been shown (Hewett et al., 2005) to be a risk factor for ACL injury. These again are important considerations in the return-to-sport decision-making process for this population post-surgery.

Based on the above information, it would appear that at 9–12 months following an ACL reconstruction, there is still a large number of individuals who are not meeting muscle and hop performance parameters, and these parameters are further impacted by fatigue. Thus, an important question is whether the training programmes being prescribed to these patients, particularly those related to strength and endurance training, are meeting the criteria required to best improve muscle performance deficits (loading, repetitions, sets and frequency). There are a number of factors which influence the restoration of muscle performance and function, including: the presence of arthrogenic muscle inhibition post-surgery (Rice & McNair, 2010); the level of involvement in prehabilitation (Eitzen, Moksnes, Snyder-Mackler, & Risberg, 2010; Grindem et al., 2015); the presence of concomitant injuries; and the adherence to and level of supervision in rehabilitation post-surgery (Ebert et al., 2018). Whilst the influence of these factors on the restoration of muscle performance post-operatively has not been proven exclusively, they may explain some of the persistent deficits in hamstring endurance and hop performance under fatigue seen across the current cohort at 10.5 months post-surgery.

Considering these findings, it would seem more appropriate that, rather than focusing on individuals returning to sport at a specific time point post-surgery, a return to sport is considered when they pass specific objective criteria for muscle strength and endurance, hop performance and psychological readiness. Given the widespread understanding that there is an increased incidence of injury during the final stages of a sporting game/event (Dugan & Frontera, 2000; Ostenberg & Roos, 2000), it is of paramount importance that we assess and act accordingly to address notable deficits in the ACL-reconstructed leg when fatigued, to ultimately reduce the potential for injury to the graft. Testing under fatigued conditions should be considered for return-to-sport testing.

## 5.6 Limitations of the Study

There are a number of limitations of the current study. Firstly, the isokinetic dynamometer used to complete strength and endurance testing is not a piece of equipment that is readily available in most physiotherapy clinics in New Zealand, and therefore this is a barrier to establishing the test in clinical practice. However, due to the high reliability and validity of the isokinetic dynamometer, it was thought to be the most appropriate tool to measure strength and endurance, particularly in a test protocol which has not been researched previously in this population. Further research investigating hamstring endurance capability utilising gym-based weight equipment is warranted and could easily be undertaken using equipment such as a weights stack and a metronome, particularly as the dependant variable is simply the number of repetitions completed. Pilot testing showed this measure to be valid and reliable. Another limitation was utilising a single joint angular velocity on the isokinetic dynamometer for hamstring endurance testing, as individuals play different sports at a range of different joint angular velocities. However, a single speed for testing was chosen as the hamstring endurance test was a lengthy and challenging test, and having the additional time and complexity of working at different angular velocities was thought to be too demanding within a single session. Next, the systematic approach to inducing fatigue commencing at 40% maximum voluntary effort and increasing in 10% increments every 2 minutes is not typical of athletic situations in which fatigue becomes apparent. However, it is very difficult to include all types/modes of fatigue into one fatigue test that is sufficiently standardised and hence more likely to have good reliability. Concerning measuring the effects of fatigue, it was not possible to test all five hop tests immediately after the fatigue test without having notable recovery in hamstring performance. So, two were chosen based upon their reported validity and reliability. Finally, the study did not include participants less than 20 years of age, a group that have been increasingly targeted for ACL reconstruction surgery in recent years. This was due to the difficulty in obtaining ethics approval for teenagers.

## 5.7 Summary and Conclusions

The purpose of this study was three-fold. Firstly, the investigation looked at the difference between hamstring endurance of the ACL-injured leg at 9–12 months after an ACL reconstruction with a hamstring graft, and both the uninjured leg and a healthy control leg matched for age, gender and activity level. A significant deficit of 18% in hamstring endurance was found between the injured and uninjured legs. Sixty-three percent of the current cohort achieved an LSI of greater than 90%, the requirement for muscle performance for a safe return to some sports. These findings are novel and provide initial evidence for the inclusion of muscle endurance exercises in ACL post-surgical rehabilitation programmes. Intervention trials would provide further conclusive support or otherwise.

Secondly, the relationship between hamstring endurance (both absolute values and LSI values) and function (both self-reported and during functional performance hop tests) was investigated. No significant relationship was found between hamstring endurance and any of the measures of function utilised. It is thought that hop performance and perceived function are likely to be influenced by more than just the parameters associated with hamstring endurance capability, and may explain these results.

Finally, hop performance under hamstring fatigue was investigated for the injured leg, uninjured leg, and a healthy control leg. A significant difference in hop performance was only found between the injured and uninjured legs post-fatigue. There was an 11% deficit in single hop for distance and a 7% deficit in triple hop for distance performance post-fatigue between legs. In addition, there was a significant decline in hop performance across all legs when comparing pre-fatigue and post-fatigue measures. Furthermore, the percentage of people passing return-to-sport hop test criteria was reduced from 50% to 33% when under fatigued conditions. These results are again novel and deserve consideration in respect of undertaking return-to-sport testing in a fatigued state.

## 5.8 Clinical Implications

Muscle endurance capability is an important aspect of muscle function for sports and recreational activities and, based on the results of this study, hamstring endurance was not restored to normal levels 9–12 months after an ACL reconstruction with a hamstring tendon graft. Given the role the hamstring muscle plays in improving knee joint stability, these initial results may guide physiotherapists working in ACL rehabilitation to address hamstring endurance more formally during the rehabilitation process.

To date, LSI scores ranging from 90% to 100% are utilised as an appropriate cut-off to determine normal function across strength and hop performance tests. The results of this study indicate that there are greater deficits in hop performance under fatigued conditions compared to non-fatigued conditions at 9–12 months post-surgery. Given the notable number of individuals reinjuring their operated knee in the first 2 years post-surgery, perhaps assessing return-to-sport criteria under standardised fatigued conditions would be a better metric for identifying deficits in this population prior to the return to sport.

## 5.9 Future Research

A number of potential research projects were identified from the current study:

1. The inclusion of quadriceps endurance testing to investigate and compare BPTB grafts and a hamstring tendon graft group at 9–12 months post-surgery would be a valuable development of the present study. This would highlight any differences in muscle endurance capability between graft groups, and would also provide further evidence concerning quadriceps endurance deficits post-surgery.

2. For clinical utility, the development of a testing protocol that incorporates both quadriceps and hamstring endurance and utilises the same principles as the current protocol, but which could be undertaken in a weight-training environment, would be beneficial and more clinically relevant to health professionals working in the area of ACL rehabilitation. Similarly, the development of a fatiguing protocol that involved muscle work for the whole lower limb (e.g., hops, running and jumping activities) would provide a closer resemblance to activities undertaken in sports.

3. A study of the impact of fatigue on lower-limb biomechanics (kinetics and kinematics) during the hopping tasks at 9–12 months post-surgery would enhance our knowledge on the effect of fatigue on lower-limb performance in this group, and would add to the breadth of knowledge regarding re-injury risk in this

population at this time point. This may further influence rehabilitation protocols for this population. Additionally, an assessment of limb alignment during hop tasks might be incorporated in return-to-sport criteria and could prove valuable in identifying those at risk of re-injury.

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Wilk, K., Romaniello, W., Soscia, S., Arrigo, C., & Andrews, J. (1994). The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. *Journal of Orthopaedic and Sports Physical Therapy, 20*(2), 60—73. doi:10.2519/jospt.1994.20.2.60

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Wollin, M., Thorborg, K., & Pizzari, T. (2017). The acute effect of match play on hamstring strength and lower limb flexibility in elite youth football players. *Scandinavian Journal of Medicine and Science in Sports, 27*(3), 282—288. doi:10.1111/sms.12655

Yanagawa, T., Shelburne, K., Serpas, F., & Pandy, M. (2002). Effect of hamstrings muscle action on stability of the ACL-deficient knee in isokinetic extension exercise. *Clinical Biomechanics, 17*(9-10), 705—712. doi:10.1016/S0268-0033(02)00104-3

Zwolski, C., Schmitt, L., Thomas, S., Hewett, T., & Paterno, M. (2016). The utility of limb symmetry indices in return-to-sport assessment in patients with bilateral anterior cruciate ligament reconstruction. *American Journal of Sports Medicine, 44*(8), 2030—2038. doi:10.1177/0363546516645084

# Appendices

## Appendix A: Ethics Approval

**AUTEC Secretariat**
Auckland University of Technology
D-88, WU406 Level 4 WU Building City Campus
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

11 December 2017

Peter McNair
Faculty of Health and Environmental Sciences

Dear Peter

Re Ethics Application: **17/423 Endurance of the hamstring muscles 9-12 months post anterior cruciate ligament (ACL) reconstruction with a hamstring graft: a cross sectional inter-limb comparison**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 11 December 2020.

**Standard Conditions of Approval**

1. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/researchethics.
2. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/researchethics.
3. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/researchethics.
4. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation then you are responsible for obtaining it. You are reminded that it is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard.

For any enquiries, please contact ethics@aut.ac.nz

Yours sincerely,

Kate O'Connor
Executive Manager
**Auckland University of Technology Ethics Committee**

Cc: nuala.grace@gmail.com

## AUTEC Secretariat

Auckland University of Technology
D-88, WU406 Level 4 WU Building City Campus
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics


23 March 2018

Peter McNair
Faculty of Health and Environmental Sciences

Dear Peter

Re: Ethics Application: **17/423 Endurance of the hamstring muscles 9-12 months post anterior cruciate ligament (ACL) reconstruction with a hamstring graft: a cross sectional inter-limb comparison**

Thank you for your request for approval of an amendment to your ethics application.

The minor amendment to the data collection protocol is approved.

I remind you of the Standard Conditions of Approval.

6. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/researchethics.
7. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/researchethics.
8. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/researchethics.
9. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
10. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation then you are responsible for obtaining it.

For any enquiries please contact ethics@aut.ac.nz

Yours sincerely,

Kate O'Connor
Executive Manager
**Auckland University of Technology Ethics Committee**

Cc: nuala.grace@gmail.com

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

## Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics


17 June 2019

Peter McNair
Faculty of Health and Environmental Sciences

Dear Peter

Re: Ethics Application: **17/423 Endurance of the hamstring muscles 9-12 months post anterior cruciate ligament (ACL) reconstruction with a hamstring graft: a cross sectional inter-limb comparison**

Thank you for your request for approval of an amendment to your ethics application.

The amendment to the eligibility (age range) is approved.

I remind you of the **Standard Conditions of Approval**.

11. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
12. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/research/researchethics.
13. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/research/researchethics.
14. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/research/researchethics.
15. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
16. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation then you are responsible for obtaining it. If the research is undertaken outside New Zealand, you need to meet all locality legal and ethical obligations and requirements.

For any enquiries please contact ethics@aut.ac.nz

Yours sincerely,

Kate O'Connor
Executive Manager
**Auckland University of Technology Ethics Committee**

Cc: nuala.grace@gmail.com

## Appendix B: Study Advertisements

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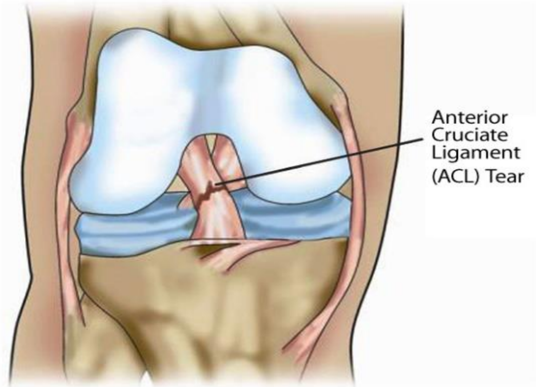
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU




# A study to examine the endurance of the hamstring muscles after surgery to reconstruct the anterior cruciate ligament (ACL) of the knee.

## Volunteers required!

- This is part of a physiotherapy research project to investigate the endurance of the hamstring muscles after surgery to reconstruct the anterior cruciate ligament (ACL) of the knee using the hamstring muscle as the graft
- Participants with an anterior cruciate ligament (ACL) injury who have had surgery to reconstruct the ligament, using a hamstring graft, within the past 12 months are required and invited to apply
- Participants must have clearance from their surgeon or physiotherapist to participate in exercise and rehabilitation in order to be eligible for participation
- Participants must be able to understand written and spoken English, and must be aged 20-45 years
- Participants must not have any known neurological or cardiovascular conditions, and other than anterior cruciate ligament (ACL) reconstruction surgery, must not have any other known bone, joint or muscle conditions, and must not have had any other previous knee injury or knee surgery

For further information please contact:

**Contact Nuala:**
P: 09 4891020
M: 0211788973
E: nuala.grace@gmail.com

**Contact Nuala:**
P: 09 4891020
M: 0211788973
E: nuala.grace@gmail.com

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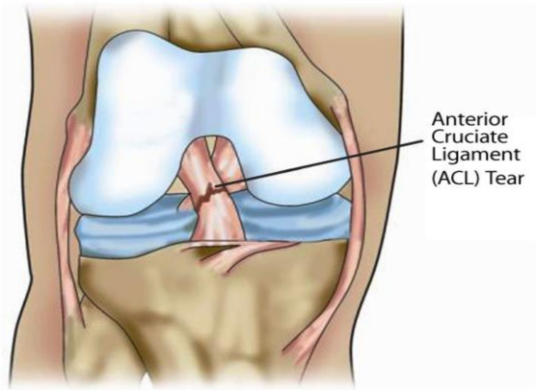
TE WĀNANGA ARONUI
O TĀMAKI MAKAU RAU




# A study to examine the endurance of the hamstring muscles after surgery to reconstruct the anterior cruciate ligament (ACL) of the knee.

## Volunteers required!

- This is part of a physiotherapy research project to investigate the endurance of the hamstring muscles after surgery to reconstruct the anterior cruciate ligament (ACL) of the knee, using the hamstring muscle as the graft
- Participants who have not had any knee injuries on either leg are required
- Participants must be able to understand written and spoken English, and must be aged 20-45 years
- Participants must not have any known neurological or cardiovascular conditions, must not have any known bone, joint or muscle condition, and must not have had any previous knee injuries or knee surgery

For further information please contact:

**Contact Nuala:**
P: 09 4891020
M: 0211788973
E: nuala.grace@gmail.com

**Contact Nuala:**
P: 09 4891020
M: 0211788973
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E: nuala.grace@gmail.com

**Contact Nuala:**
P: 09 4891020
M: 0211788973
E: nuala.grace@gmail.com

## Appendix C: Study Consent Forms

# Consent Form

Healthy Participant Group for Phase 1 of the Study (Reliability Testing)

*Project title:* Endurance of the hamstring muscles 9-12 months post anterior cruciate ligament reconstruction with a hamstring graft: a cross sectional inter-limb comparison

*Project Supervisor:* Professor Peter McNair

*Researcher:* Nuala Grace

○ I have read and understood the information provided about this research project in the Information Sheet dated 15th November 2017.

○ I have had an opportunity to ask questions and to have them answered.

○ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.

○ I understand that if I withdraw from the study then I will be offered the choice between having any data that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.

○ I do not suffer from high blood pressure, any respiratory condition (mild asthma excluded), any neurological illness or cardiovascular disease, any infection, any notable knee injury of either leg, any history of low back pain in the past 6 months, or any previous history of recurring hamstring injury of either leg that impairs my physical performance.

○ I agree to take part in this research.

○ I wish to receive a summary of the research findings (please tick one): Yes○ No○

Participant's signature: .....................................................................................................................

Participant's name: .....................................................................................................................

Participant's contact details (if appropriate):

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Date:

***Approved by the Auckland University of Technology Ethics Committee on 11th December 2017***

***AUTEC Reference number* 17/423**

*Note: The Participant should retain a copy of this form*

# Consent Form

Knee Injured Group for Phase 2 of the Study

*Project title:* Endurance of the hamstring muscles 9-12 months post anterior cruciate ligament reconstruction with a hamstring graft: a cross sectional inter-limb comparison

*Project Supervisor:* Professor Peter McNair

*Researcher:* Nuala Grace

○ I have read and understood the information provided about this research project in the Information Sheet dated 15th November 2017.

○ I have had an opportunity to ask questions and to have them answered.

○ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.

○ I understand that if I withdraw from the study then I will be offered the choice between having any data that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.

○ I do not suffer from high blood pressure, any respiratory condition (mild asthma excluded), any neurological illness or cardiovascular disease, any infection, any history of low back pain in the past 6 months, any previous history of recurring hamstring injury of either leg, co-existing grade IV chondral lesion (full thickness) and/or large meniscal tear repair in my ACL reconstructed knee, or previous notable knee injury in either leg that impairs my physical performance.

○ I have been given clearance by my orthopaedic surgeon and/or physiotherapist to participate in rehabilitation and exercise

○ I agree to take part in this research.

○ I wish to receive a summary of the research findings (please tick one): Yes○ No○

Participant's signature: .....................................................................................................................

Participant's name: .....................................................................................................................

Participant's contact details (if appropriate):

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Date:

***Approved by the Auckland University of Technology Ethics Committee on 11th December 2017***

***AUTEC Reference number* 17/423**

*Note: The Participant should retain a copy of this form*

# Consent Form

Healthy Participant Group for Phase 2 of the Study

*Project title:* Endurance of the hamstring muscles 9-12 months post anterior cruciate ligament reconstruction with a hamstring graft: a cross sectional inter-limb comparison

*Project Supervisor:* Professor Peter McNair

*Researcher:* Nuala Grace

○ I have read and understood the information provided about this research project in the Information Sheet dated 15th November 2017.

○ I have had an opportunity to ask questions and to have them answered.

○ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.

○ I understand that if I withdraw from the study then I will be offered the choice between having any data that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.

○ I do not suffer from high blood pressure, any respiratory condition (mild asthma excluded), any neurological illness or cardiovascular disease, any infection, any previous notable knee injury of either leg, any history of low back pain in the past 6 months, or any previous history of recurring hamstring injury of either leg that impairs my physical performance.

○ I agree to take part in this research.

○ I wish to receive a summary of the research findings (please tick one): Yes○ No○

Participant's signature: ..................................................................................................................

Participant's name: ..................................................................................................................

Participant's contact details (if appropriate):

……………………………………………………………………………………..

……………………………………………………………………………………..

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……………………………………………………………………………………..

Date:

***Approved by the Auckland University of Technology Ethics Committee on 11th December 2017***

***AUTEC Reference number* 17/423**

*Note: The Participant should retain a copy of this form*

## Appendix D: Participant Information Sheets

# Participant Information Sheet

**Phase 1: Reliability Testing for Healthy Participants**

**Date Information Sheet Produced:**

15th November 2017

**Project Title**

Endurance of the hamstring muscles 9-12 months post anterior cruciate ligament reconstruction with a hamstring graft: a cross sectional inter-limb comparison

**An Invitation**

My name is Nuala Grace. I am a physiotherapist and Masters student at the Health and Rehabilitation Research Institute, Faculty of Health and Environmental Sciences, School of Clinical Sciences at AUT. I would like to invite you to take part in our project called *"Endurance of the hamstring muscles 9-12 months post anterior cruciate ligament reconstruction with a hamstring graft: a cross sectional inter-limb comparison'*. This research project will help me gain my qualification of a Masters in Health Science. Participation in this study is voluntary and will not affect your ability to access healthcare and physiotherapy services in the future. You may withdraw from the study at any time point without any consequence.

**What is the purpose of this research?**

The purpose of this research project is to examine the endurance capability of the hamstring muscles 9-12 months after anterior cruciate ligament (ACL) reconstruction of the knee with a hamstring tendon graft. Muscle endurance capability is important in most sport and recreational activities. This research will be part of a Masters thesis. This phase of the research project involves establishing the consistency of scores for hamstring endurance using a specific endurance test, which is explained in more detail below.

**How was I identified and why am I being invited to participate in this research?**

You have responded to an advertisement or have been informed verbally of this study which directed you to making contact with myself, Nuala Grace. You are a potential healthy participant with no history of knee injury in either leg, and aged between 20-45 years. You may be excluded from this study if you have any known neurological, cardiovascular, or bone and joint diseases, if you have had previous knee injury/surgery, or if you do not understand spoken and/or written English.

**How do I agree to participate in this research?**

You will be required to complete a written consent form. This will be done on the day of testing, prior to any testing. The testing session will be scheduled once you have agreed to participate in this study.

Your participation in this research is voluntary (it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you. You are able to withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

**What will happen in this research?**

If you choose to participate in this study, you will be required to attend two sessions at one of two locations: the YMCA, Akoranga Drive, Northcote, Auckland ***or*** at the Biomechanics Lab, Health and Rehabilitation Institute, AUT Northshore Campus, Akoranga Drive, Northcote, Auckland. These sessions will occur no more than 1-2 weeks apart. Each session will last from 45-60 minutes. Both sessions will follow the same format. At the first session you will also be asked to complete some written questionnaires relating to your knee and health.

Once you have completed the questionnaires, the strength of the muscles that move your knee joint will be tested using an isokinetic dynamometer machine (see image below). You will sit on the machine and your chest, hips and one of your legs will be strapped in as shown in the picture. Your strength will be assessed by bending and straightening your knee with as much effort as you can. The results will be recorded on the computer. Then your hamstring muscle endurance will be tested using the same piece of equipment, and the same movements. However, this test will assess how many bending and straightening movements you can do before you fatigue. This test usually takes approximately 10 minutes. You will be given careful instructions throughout the tests, and there will be an opportunity to warm up and practice the movements prior to the tests. You can stop at any time during the tests.

**What are the discomforts and risks?**

There are no significant risks associated with the tests. However, there is a risk that you will experience some mild discomfort in the muscles surrounding the knee. This discomfort should not be more than that experienced when your muscles have worked hard over a 10 minute period. The tests are designed to mimic normal daily and sporting activities (e.g. stairs climbing; running; jumping) and therefore you should not experience anything greater than that described above.

**How will these discomforts and risks be alleviated?**

If you encounter greater discomfort than that described above during testing you may stop. A physiotherapist who has the appropriate knowledge and skill to manage pain, swelling and irritation of the knee will be carrying out all tests, and thus will be able to provide appropriate advice to you on how to manage any discomfort. You can also contact the physiotherapist at the number indicated below within the Researcher Contact details at the end of this information sheet.


**What are the benefits?**

This study is part of a Masters thesis and will help me to gain a Masters in Health Science.

There are no direct benefits for you by participating in this study. The results of the study will provide more information concerning the consistency of the scores related to your hamstring endurance using the test outlined above. If the results show good consistency, then the test will be used in phase two of the project where the tests are repeated on individuals with a reconstructed knee joint. This 2nd phase may help to guide rehabilitation for anterior cruciate ligament (ACL) reconstruction in the future, reduce the risk of re-injury, and provide more information about a safe return to sport after knee surgery.

**What compensation is available for injury or negligence?**

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for your injury may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

**How will my privacy be protected?**

When you enter the study, you will be given an identification code and your name will not be used on data/records related to the data collected. The consent form will contain both your name and identification code and this will be stored securely under lock and key at the School of Clinical Sciences, AUT Northshore Campus. Only the primary researcher and her supervisors will have access to this form. Any data collected in writing will contain your unique identification code only. You will not be identifiable in the final report.

**What are the costs of participating in this research?**

There are no direct costs associated with participation in this study, only your personal time. The testing session is expected to last no more than 60 minutes. You will receive a small token of appreciation for your time and participation.

**What opportunity do I have to consider this invitation?**

You have 2-4 weeks to consider this invitation. We will contact you 7 days after you receive this information sheet. If you require more time to consider this invitation, just let us know.

**Will I receive feedback on the results of this research?**

A one-page summary of the study results will be sent to you via post or email upon completion of the study and data analysis unless you indicate otherwise on your consent form.

**What do I do if I have concerns about this research?**

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Peter McNair, *peter.mcnair@aut.ac.nz* , +64 9 921 9999 ext 7143

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, *ethics@aut.ac.nz* , 921 9999 ext 6038.

**Whom do I contact for further information about this research?**

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

**Researcher Contact Details:**

Nuala Grace, AUT University North Shore Campus
Ph: 0211788973
Email: nuala.grace@gmail.com

**Project Supervisor Contact Details:**

Dr Peter McNair, AUT University North Shore Campus
Ph: +64 9 921 9999 ext 7143
Email: peter.mcnair@aut.ac.nz

***Approved by the Auckland University of Technology Ethics Committee on 11th December 2017***

***AUTEC Reference number* 17/423**

# Participant Information Sheet

**Phase 2: Hamstring Endurance and Hop Performance Testing for Knee Injured Participants**

**Date Information Sheet Produced:**

15th November 2017

**Project Title**

Endurance of the hamstring muscles 9-12 months post anterior cruciate ligament reconstruction with a hamstring graft: a cross sectional inter-limb comparison

**An Invitation**

My name is Nuala Grace. I am a physiotherapist and Masters student at the Health and Rehabilitation Research Institute, Faculty of Health and Environmental Sciences, School of Clinical Sciences at AUT. I would like to invite you to take part in our project called *"Endurance of the hamstring muscles 9-12 months post anterior cruciate ligament reconstruction with a hamstring graft: a cross sectional inter-limb comparison'*. This research project will help me gain my qualification of a Masters in Health Science. Participation in this study is voluntary and will not affect your ability to access healthcare and physiotherapy services in the future. You may withdraw from the study at any time point without any consequence.

**What is the purpose of this research?**

The purpose of this research project is to examine the endurance capability of the hamstring muscles 9-12 months after anterior cruciate ligament (ACL) reconstruction of the knee with a hamstring tendon graft, and compare this to ones uninjured leg. Hamstring muscle endurance will also be compared to the participants knee function. Muscle endurance capability is important in most sport and recreational activities, and the hamstring muscles are important in preventing injury to the new graft. Therefore, it is important to understand the endurance capabilities of the hamstring muscles 9-12 months after surgery, as this is the common time point for people to be given clearance to return to sports. This research will be part of a Masters thesis and will be written up for publication in an international journal. The results of this research may also be presented at national and international physiotherapy and sports medicine conferences. This phase of the research project involves assessing hamstring muscle endurance and knee function using a series of hop tests and some written questionnaires.

**How was I identified and why am I being invited to participate in this research?**

You have responded to an advertisement or been informed verbally of this study which directed you to making contact with myself, Nuala Grace. You will have had a reconstruction of your anterior cruciate ligament using a graft of your hamstring tendon. You will have clearance from your orthopaedic surgeon and/or physiotherapist to participate in rehabilitation and exercise. You may be excluded from this study if you have any known neurological, cardiovascular, or bone and joint diseases, if you have had a previous knee injury or knee surgery, or if you do not understand spoken and/or written English.

**How do I agree to participate in this research?**

You will be required to complete a written consent form prior to participating in this study. This will be done on the day of testing, prior to any testing. The testing session will be scheduled once you have agreed to participate in this study.

Your participation in this research is voluntary (it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you. You are able to withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

**What will happen in this research?**

If you choose to participate in this study, you will be required to attend one session at one of two locations: the YMCA, Akoranga Drive, Northcote, Auckland ***or*** at the Biomechanics Lab, Health and Rehabilitation Institute, AUT Northshore Campus, Akoranga Drive, Northcote, Auckland. This session will last anywhere from 60-90 minutes. At this session you will be asked to complete a consent form for this study before testing starts, and some written questionnaires relating to your knee and health.

Once you have completed the questionnaires, you will be asked to complete 5 different hop tests to measure the function of both of your legs. These tests will involve hopping on one leg. The distance hopped, number of hops completed in a given time, height jumped, or the time taken to hop a specified distance (3-6 metres) will be measured. Once you have completed these hop tests, the strength of the muscles that move your knee joint will be tested using an isokinetic dynamometer machine (see image below). You will sit on the machine and your chest, hips and one of your legs will be strapped in as shown in the picture. Your strength will be assessed by bending and straightening your knee with as much effort as you can. The results will be recorded on the computer. Your muscle strength will be assessed on both legs. Then your hamstring muscle endurance will be tested using the same piece of equipment, and the same movements. However, this test will assess how many bending and straightening movements you can do. This test usually takes approximately 10 minutes per leg and will be assessed on both legs. You will be given careful instructions throughout the tests, and there will be an opportunity to practice the movements and warm up prior to the formal test. Immediately upon completion of the endurance test on each leg, you will be asked to repeat two of the hop tests performed earlier while your hamstring muscle is still fatigued.

**What are the discomforts and risks?**

There are no significant risks associated with the tests. These strength and hopping tests are recommended for individuals returning to sports following an anterior cruciate ligament reconstruction of the knee to assess knee function and recovery. However, there is a risk that you will experience some mild discomfort in the knee or in the muscles surrounding the knee. This discomfort should not be more than that experienced when your muscles have worked hard over a 10 minute period. The tests are designed to mimic normal daily and sporting activities (e.g. stairs climbing; cycling, running; jumping) and therefore you should not experience anything greater than what you would experience during these tasks.


**How will these discomforts and risks be alleviated?**

If you encounter greater discomfort than that described above during testing you may stop. A physiotherapist who has the appropriate knowledge and skill to manage pain, swelling and irritation of the knee will be carrying out all tests and thus will be able to provide appropriate advice to you on how to manage any discomfort. You can also contact the physiotherapist at the number outlined below within the Researcher Contact details at the end of this information sheet.

**What are the benefits?**

Participation in this study will provide you with information regarding your knee muscle strength, hamstring muscle endurance and knee function. It will identify any deficits in your performance and you could use this information to improve your knee function further. This information may also help to guide rehabilitation protocols in the future, reduce the risk of re-injury, and provide more information about a safe return to sport post reconstruction surgery. This study is part of a Masters thesis, and as such will help me to gain a qualification of a Masters in Health Science.

**What compensation is available for injury or negligence?**

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for your injury may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

**How will my privacy be protected?**

When you enter the study, you will be given an identification code and your name will not be used on data/records related to the data collected. The consent form will contain both your name and identification code and this will be stored securely under lock and key at the School of Clinical Sciences, AUT Northshore Campus. Only the primary researcher and her supervisors will have access to this form. Any data collected in writing will contain your unique identification code only. You will not be identifiable in the final report.

**What are the costs of participating in this research?**

There are no direct costs associated with participation in this study, only your personal time. The testing session is expected to last no more than 90 minutes. You will receive a small token of appreciation for your time and participation.

**What opportunity do I have to consider this invitation?**

You have 2-4 weeks to consider this invitation. We will contact you 7 days after you receive this information sheet. If you require more time to consider this invitation, just let us know.

**Will I receive feedback on the results of this research?**

A one-page summary of the study results will be sent to you via post or email upon completion of the study and data analysis unless you indicate otherwise on your consent form.

**What do I do if I have concerns about this research?**

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Peter McNair, *peter.mcnair@aut.ac.nz* , +64 9 921 9999 ext 7143

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, *ethics@aut.ac.nz* , 921 9999 ext 6038.

**Whom do I contact for further information about this research?**

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows

**Researcher Contact Details:**

Nuala Grace, AUT University North Shore Campus
Ph: 0211788973
Email: nuala.grace@gmail.com

**Project Supervisor Contact Details:**

Dr Peter McNair, AUT University North Shore Campus
Ph: +64 9 921 9999 ext 7143
Email: peter.mcnair@aut.ac.nz

***Approved by the Auckland University of Technology Ethics Committee on 11th December 2017***

***AUTEC Reference number* 17/423**

# Participant Information Sheet

**Phase 2: Hamstring Endurance and Hop Performance Testing for Healthy Participants**

**Date Information Sheet Produced:**

15th November 2017

**Project Title**

Endurance of the hamstring muscles 9-12 months post anterior cruciate ligament reconstruction with a hamstring graft: a cross sectional inter-limb comparison

**An Invitation**

My name is Nuala Grace. I am a physiotherapist and Masters student at the Health and Rehabilitation Research Institute, Faculty of Health and Environmental Sciences, School of Clinical Sciences at AUT. I would like to invite you to take part in our project called *"Endurance of the hamstring muscles 9-12 months post anterior cruciate ligament reconstruction with a hamstring graft: a cross sectional inter-limb comparison'*. This research project will help me gain my qualification of a Masters in Health Science. Participation in this study is voluntary and will not affect your ability to access healthcare and physiotherapy services in the future. You may withdraw from the study at any time point without any consequence.

**What is the purpose of this research?**

The purpose of this research project is to examine the endurance capability of the hamstring muscles 9-12 months after anterior cruciate ligament (ACL) reconstruction of the knee with a hamstring tendon graft, and compare this to ones uninjured leg. Hamstring muscle endurance will also be compared to the participants knee function. Muscle endurance capability is important in most sport and recreational activities, and the hamstring muscles are important in preventing injury to the new graft. Therefore, it is important to understand the endurance capabilities of the hamstring muscles 9-12 months after surgery, as this is the common time point for people to be given clearance to return to sports. This research will be part of a Masters thesis and will be written up for publication in an international journal. The results of this research may also be presented at national and international physiotherapy and sports medicine conferences. This phase of the research project involves assessing hamstring muscle endurance and knee function using a series of hop tests and some written questionnaires.

**How was I identified and why am I being invited to participate in this research?**

You have responded to an advertisement or been informed verbally of this study which directed you to making contact with myself, Nuala Grace. You will have no history of knee injury on either leg. Data gained from this group of healthy participants (no history of knee injury) will be used to compare to both the injured leg and uninjured leg of the knee injured group to identify if there are any differences. You may be excluded from this study if you have any known neurological, cardiovascular, or bone and joint diseases, if you have had previous knee surgery, or if you do not understand spoken and/or written English.

**How do I agree to participate in this research?**

You will be required to complete a written consent form prior to participating in this study. This will be done on the day of testing, prior to any testing. The testing session will be scheduled once you have agreed to participate in this study.

Your participation in this research is voluntary (it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you. You are able to withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

**What will happen in this research?**

If you choose to participate in this study, you will be required to attend one session at one of two locations: the YMCA, Akoranga Drive, Northcote, Auckland ***or*** at the Biomechanics Lab, Health and Rehabilitation Institute, AUT Northshore Campus, Akoranga Drive, Northcote, Auckland. This session will last anywhere from 60-90 minutes. At this session you will be asked to complete a consent form for this study before testing starts, and some written questionnaires relating to your knee and health.

Once you have completed the questionnaires, you will be asked to complete 5 different hop tests to measure the function of both of your legs. These tests will involve hopping on one leg. The distance hopped, number of hops completed in a given time, height jumped, or the time taken to hop a specified distance (3-6 metres) will be measured. Once you have completed these hop tests, the strength of the muscles that move your knee joint will be tested using an isokinetic dynamometer machine (see image below). You will sit on the machine and your chest, hips and one of your legs will be strapped in as shown in the picture. Your strength will be assessed by bending and straightening your knee with as much effort as you can. The results will be recorded on the computer. Your muscle strength will be assessed on both legs. Then your hamstring muscle endurance will be tested using the same piece of equipment, and the same movements. However, this test will assess how many bending and straightening movements you can do. This test usually takes approximately 10 minutes per leg and will be assessed on both legs. You will be given careful instructions throughout the tests, and there will be an opportunity to practice the movements and warm up prior to the formal test. Immediately upon completion of the endurance test on each leg, you will be asked to repeat two of the hop tests performed earlier while your hamstring muscle is still fatigued.

**What are the discomforts and risks?**

There are no significant risks associated with the tests. However, there is a risk that you will experience some mild discomfort in the knee or in the muscles surrounding the knee. This discomfort should not be more than that experienced when your muscles have worked hard over a 10 minute period. The tests are designed to mimic normal daily and sporting activities (e.g. stairs climbing; cycling, running; jumping) and therefore you should not experience anything greater than what you would experience during these activities.


**How will these discomforts and risks be alleviated?**

If you encounter greater discomfort than that described above during testing you may stop. A physiotherapist who has the appropriate knowledge and skill to manage pain, swelling and irritation of the knee will be carrying out all tests and thus will be able to provide appropriate advice to you on how to manage any discomfort. You can also contact the physiotherapist at the number outlined below within the Researcher Contact details at the end of this information sheet.

**What are the benefits?**

There are no direct benefits for you by participating in this study. The information gained from this study may help to guide rehabilitation protocols in the future, reduce the risk of re-injury, and provide more information about a safe return to sport post-surgery. This study is part of a Masters thesis, and as such will help me to gain a qualification of a Masters in Health Science.

**What compensation is available for injury or negligence?**

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for your injury may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

**How will my privacy be protected?**

When you enter the study, you will be given an identification code and your name will not be used on data/records related to the data collected. The consent form will contain both your name and identification code and this will be stored securely under lock and key at the School of Clinical Sciences, AUT Northshore Campus. Only the primary researcher and her supervisors will have access to this form. Any data collected in writing will contain your unique identification code only. You will not be identifiable in the final report.

**What are the costs of participating in this research?**

There are no direct costs associated with participation in this study, only your personal time. The testing session is expected to last no more than 90 minutes. You will receive a small token of appreciation for your time and participation.

**What opportunity do I have to consider this invitation?**

You have 2-4 weeks to consider this invitation. We will contact you 7 days after you receive this information sheet. If you require more time to consider this invitation, just let us know.

**Will I receive feedback on the results of this research?**

A one-page summary of the study results will be sent to you via post or email upon completion of the study and data analysis unless you indicate otherwise on your consent form.

**What do I do if I have concerns about this research?**

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Peter McNair, *peter.mcnair@aut.ac.nz* , +64 9 921 9999 ext 7143

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, *ethics@aut.ac.nz* , 921 9999 ext 6038.

**Whom do I contact for further information about this research?**

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

**Researcher Contact Details:**

Nuala Grace, AUT University North Shore Campus
Ph: 0211788973
Email: nuala.grace@gmail.com

**Project Supervisor Contact Details:**

Dr Peter McNair, AUT University North Shore Campus
Ph: +64 9 921 9999 ext 7143
Email: peter.mcnair@aut.ac.nz

***Approved by the Auckland University of Technology Ethics Committee on 11th December 2017***

***AUTEC Reference number* 17/423**

## Appendix E: Questionnaire Relating to Demographic and Other Details

AUT UNIVERSITY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

**Identification Code:** ________________

**Research Study Title: Endurance of the hamstring muscles 9-12 months post anterior cruciate ligament reconstruction with a hamstring graft: a cross sectional inter-limb comparison.**

Please answer the questions below. If you have any questions relating to this document, please discuss these with the research team prior to completing the form. Please tick the box which is most appropriate to your situation. If you have had knee surgery, please answer Section 1 and Section 2. If you have not had knee surgery, please answer Section 1 only.

**Section 1:**

- Date of Birth: _____________ Ethnicity: _____________
- Gender: Male ☐ Female ☐
- Which leg is your dominant leg (which leg would you kick a football with)?

  Right ☐ Left ☐
- Occupation (Job Title): _____________ Full time or Part time: _____________
- How many hours do you work per week on average? _____________
- What percentage of your work day do you spend in the following positions:

  ☐ Sitting: ____ ☐ Standing: ____ ☐ Walking: ___

**Section 2:**

- Time since knee surgery:

  9 months ☐ 10 months ☐ 11 months ☐ 12 months ☐
- Name of surgeon: _________________
- Type of graft (hamstring or patellar tendon): ___________________
- Did you have surgery for the meniscus in your knee, and if so, was it a meniscectomy (removal of the meniscus) or meniscal repair?

  Surgery: Yes ☐ No ☐

  Type of surgery: Menisectomy ☐ Meniscal Repair ☐

- Which leg did you have knee surgery on (if appropriate)? Right ☐ Left ☐
- Did you undertake a formal rehabilitation program after your knee reconstruction surgery?

  Yes ☐ No ☐
- Did a health professional guide you through this programme, with regular input?

  ☐ Physio ☐ Surgeon ☐ GP ☐ PT ☐ Other
- How regular was this input? ______________________
- If you saw a physiotherapist after surgery, how long after surgery did this commence? _____
- How long after surgery did you see your physiotherapist for? _____________
- How many sessions per week (on average) did you have of physiotherapy? _____________
- How many times did you see your surgeon after surgery? ______________________
- Since surgery, how many sessions per week did you undertake that were exercise primarily? (including rehab based exercise) ____________________________________
- What percent of your rehabilitation was the physiotherapist or trainer working one on one with you? (Circle below)

  10 20 30 40 50 60 70 80 90 100

- Did the physiotherapy led or independent sessions involve any of the following (tick more than one if necessary)

| | | | |
|---|---|---|---|
| ☐ | Weights/resistance training for the quads and hamstrings | ☐ | Ultrasound |
| ☐ | Weights/resistance training for hip muscles | ☐ | Heat |
| ☐ | Aerobic 20-30 minutes of moderate intensity | ☐ | Massage |
| ☐ | Functional exercise training (hopping, side steps, jumping) | ☐ | Ice |
| ☐ | Muscle stimulation | ☐ | Balance training |

❖ How many months did your rehabilitation program last?

_________________________

❖ When were you allowed to return to sport/activity that you primarily participated in prior to the injury/surgery? (how many months after surgery)

_____________________________

❖ Who gave you clearance for returning to sport (tick more than one if applicable):

☐ Physiotherapist ☐ Surgeon ☐ GP ☐ Other: ____________

❖ What sport was that? __________________________

❖ Did you have a formal return to sport test (to confirm you were ready to return to sport)?

Yes ☐ No ☐

❖ If yes, did it involve strength testing of the quadriceps and hamstring muscles?

Yes ☐ No ☐

❖ If yes, did it involve running or hopping or jumping tests?

Yes ☐ No ☐

❖ If yes, did it involve any balance testing?

Yes ☐ No ☐

❖ Overall rating of knee:

Please rate the overall condition of your knee at the present time. Circle 1 number below.

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|
| | poor | | fair | | good | | | | normal |

**Poor:** I have significant limitations that affect activities of daily living

**Fair:** I have moderate limitations that affect activities of daily living, no sports possible

**Good:** I have some limitations with sports but I can participate; I compensate.

**Normal/excellent:** I am able to do whatever I wish (any sport) with no problems.

## Appendix F: Knee Injury and Osteoarthritis Outcome Score



# KOOS KNEE SURVEY

Today's date: _____/______/______ Date of birth: _____/______/______

Name: ________________________________________________

**INSTRUCTIONS:** This survey asks for your view about your knee. This information will help us keep track of how you feel about your knee and how well you are able to perform your usual activities.
Answer every question by ticking the appropriate box, only <u>one</u> box for each question. If you are unsure about how to answer a question, please give the best answer you can.

**Symptoms**
These questions should be answered thinking of your knee symptoms during the **last week**.

S1. Do you have swelling in your knee?

| Never | Rarely | Sometimes | Often | Always |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

S2. Do you feel grinding, hear clicking or any other type of noise when your knee moves?

| Never | Rarely | Sometimes | Often | Always |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

S3. Does your knee catch or hang up when moving?

| Never | Rarely | Sometimes | Often | Always |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

S4. Can you straighten your knee fully?

| Always | Often | Sometimes | Rarely | Never |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

S5. Can you bend your knee fully?

| Always | Often | Sometimes | Rarely | Never |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

**Stiffness**
The following questions concern the amount of joint stiffness you have experienced during the **last week** in your knee. Stiffness is a sensation of restriction or slowness in the ease with which you move your knee joint.

S6. How severe is your knee joint stiffness after first wakening in the morning?

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

S7. How severe is your knee stiffness after sitting, lying or resting **later in the day**?

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

## Pain

P1. How often do you experience knee pain?

| Never | Monthly | Weekly | Daily | Always |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

What amount of knee pain have you experienced the **last week** during the following activities?

P2. Twisting/pivoting on your knee

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

P3. Straightening knee fully

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

P4. Bending knee fully

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

P5. Walking on flat surface

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

P6. Going up or down stairs

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

P7. At night while in bed

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

P8. Sitting or lying

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

P9. Standing upright

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

## Function, daily living

The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A1. Descending stairs

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A2. Ascending stairs

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A3. Rising from sitting

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A4. Standing

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A5. Bending to floor/pick up an object

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A6. Walking on flat surface

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A7. Getting in/out of car

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A8. Going shopping

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A9. Putting on socks/stockings

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A10. Rising from bed

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A11. Taking off socks/stockings

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A12. Lying in bed (turning over, maintaining knee position)

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A13. Getting in/out of bath

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A14. Sitting

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

A15. Getting on/off toilet

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A16. Heavy domestic duties (moving heavy boxes, scrubbing floors, etc)

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| □ | □ | □ | □ | □ |

A17. Light domestic duties (cooking, dusting, etc)

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| □ | □ | □ | □ | □ |

**Function, sports and recreational activities**

The following questions concern your physical function when being active on a higher level. The questions should be answered thinking of what degree of difficulty you have experienced during the **last week** due to your knee.

SP1. Squatting

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| □ | □ | □ | □ | □ |

SP2. Running

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| □ | □ | □ | □ | □ |

SP3. Jumping

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| □ | □ | □ | □ | □ |

SP4. Twisting/pivoting on your injured knee

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| □ | □ | □ | □ | □ |

SP5. Kneeling

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| □ | □ | □ | □ | □ |

**Quality of Life**

Q1. How often are you aware of your knee problem?

| Never | Monthly | Weekly | Daily | Constantly |
|---|---|---|---|---|
| □ | □ | □ | □ | □ |

Q2. Have you modified your life style to avoid potentially damaging activities to your knee?

| Not at all | Mildly | Moderately | Severely | Totally |
|---|---|---|---|---|
| □ | □ | □ | □ | □ |

Q3. How much are you troubled with lack of confidence in your knee?

| Not at all | Mildly | Moderately | Severely | Extremely |
|---|---|---|---|---|
| □ | □ | □ | □ | □ |

Q4. In general, how much difficulty do you have with your knee?

| None | Mild | Moderate | Severe | Extreme |
|---|---|---|---|---|
| □ | □ | □ | □ | □ |

***Thank you very much for completing all the questions in this questionnaire.***

## Appendix G: Lower-Limb Task Questionnaire



### APPENDIX 1: LOWER-LIMB TASKS QUESTIONNAIRE

ACTIVITIES OF DAILY LIVING SECTION

**Patient:** ______________ **Date:**____________

**INSTRUCTIONS**

Please rate your ability to do the following activities in the past 24 hours by circling the number below the appropriate response.

If you did not have the opportunity to perform an activity in the **past 24 hours**, please make your *best estimate* on which response would be the most accurate.

Please also rate how important each task is to you in your daily life according to the following scale:

**1. = Not important**
**2. = Mildly important**
**3. = Moderately important**
**4. = Very important**

Please answer all questions.

| | | NO DIFFICULTY | MILD DIFFICULTY | MODERATE DIFFICULTY | SEVERE DIFFICULTY | UNABLE | IMPORTANCE OF TASK | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. | Walk for 10 minutes | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 2. | Walk up or down 10 steps (1 flight) | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 3. | Stand for 10 minutes | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 4. | Stand for a typical work day | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 5. | Get on and off a bus | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 6. | Get up from a lounge chair | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 7. | Push or pull a heavy trolley | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 8. | Get in and out of a car | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 9. | Get out of bed in the morning | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 10. | Walk across a slope | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| | | | TOTAL (/40) : ____ | | | | | | | |

RECREATIONAL ACTIVITIES SECTION

**Patient:** ______________ **Date:**____________

**INSTRUCTIONS**

Please rate your ability to do the following activities in the past 24 hours by circling the number below the appropriate response.

If you did not have the opportunity to perform an activity in the **past 24 hours**, please make your *best estimate* on which response would be the most accurate.

Please also rate how important each task is to you in your daily life according to the following scale:

**1. = Not important**
**2. = Mildly important**
**3. = Moderately important**
**4. = Very important**

Please answer all questions.

| | | NO DIFFICULTY | MILD DIFFICULTY | MODERATE DIFFICULTY | SEVERE DIFFICULTY | UNABLE | IMPORTANCE OF TASK | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. | Jog for 10 minutes | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 2. | Pivot or twist quickly while walking | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 3. | Jump for distance | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 4. | Run fast/sprint | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 5. | Stop and start moving quickly | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 6. | Jump upwards and land | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 7. | Kick a ball hard | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 8. | Pivot or twist quickly while running | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 9. | Kneel on both knees for 5 minutes | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| 10. | Squat to the ground/floor | 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 | 4 |
| | | | TOTAL (/40): ____ | | | | | | | |

## Appendix H: Cincinnati Knee Rating System, Sports Activity and Function Form

| Patient Name | Involved Knee | Date of Visit |
|---|---|---|
| | Right____ Left____ | mo____ day____ yr____ |

### Sports Activity Scale

***Check the box which describes your level of sports activity before your original knee injury. Then, check the box which describes your level of sports activity at this time.***

| BEFORE INJURY | | CURRENT LEVEL | |
|---|---|---|---|
| | | | **Level I (participates 4-7 days/week)** |
| ☐ | 100 | ☐ | Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer) |
| ☐ | 95 | ☐ | Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling) |
| ☐ | 90 | ☐ | No running, twisting, jumping (cycling, swimming) |
| | | | **Level II (participates 1-3 days/week)** |
| ☐ | 85 | ☐ | Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer) |
| ☐ | 80 | ☐ | Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling) |
| ☐ | 75 | ☐ | No running, twisting, jumping (cycling, swimming) |
| | | | **Level III (participates 1-3 times/month)** |
| ☐ | 65 | ☐ | Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer) |
| ☐ | 60 | ☐ | Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling) |
| ☐ | 55 | ☐ | No running, twisting, jumping (cycling, swimming) |
| | | | **Level IV (no sports)** |
| ☐ | 40 | ☐ | I perform activities of daily living without problems |
| ☐ | 20 | ☐ | I have moderate problems with activities of daily living |
| ☐ | 0 | ☐ | I have severe problems with activities of daily living; on crutches, full disability |

*Highest Level (before injury)* ____/ 100

*Highest Level (current)* ____/ 100

### Change in Sports Activities

***Check the box which best describes any change you have had in sports activities since your injury / surgery.***

My sports activities have:

**Not Changed**
*If yes, check one box below:*
- ☐ I have no / slight problems (*c*)
- ☐ I have moderate / significant problems (*d*)

**Decreased**
*If yes, check one box below:*
- ☐ I now have no / slight problems (*e*)
- ☐ I now have moderate / significant problems (*d*)
- ☐ For reasons not related to my knee (*g*)

**Stopped – given up all sports**
*If yes, check one box below:*
- ☐ I have moderate / significant problems when I play sports (*f*)
- ☐ For reasons not related to my knee (*g*)

*Level*________

### Function ADL

***Check the problems you have during:***

**1. Walking**
*check one box:*
- 40 ☐ normal, unlimited
- 30 ☐ some limitations
- 20 ☐ only 3-4 blocks possible
- 0 ☐ less than 1 block; cane, crutch

**2. Stairs**
*check one box:*
- 40 ☐ normal, unlimited
- 30 ☐ some limitations
- 20 ☐ only 11-30 steps possible
- 0 ☐ only 1-10 steps possible

**3. Squatting / kneeling**
*check one box:*
- 40 ☐ normal, unlimited
- 30 ☐ some limitations
- 20 ☐ only 6-10 possible
- 0 ☐ only 0-5 possible

*Level* _____/ 3=______

### Function Sports

***Check the problems you have during:***

**1. Straight running**
*check one box:*
- 100 ☐ fully competitive
- 80 ☐ some limitations, guarding
- 60 ☐ definite limitations, half speed
- 40 ☐ not able to do

**2. Jumping / landing on affected leg**
*check one box:*
- 100 ☐ fully competitive
- 80 ☐ some limitations, guarding
- 60 ☐ definite limitations, half speed
- 40 ☐ not able to do

**3. Hard twists / cuts / pivots**
*check one box:*
- 100 ☐ fully competitive
- 80 ☐ some limitations, guarding
- 60 ☐ definite limitations, half speed
- 40 ☐ not able to do

*Level* _____/ 3=______

### Problems with Sports

***Describe the problems you would have with your knee after participating for one hour without guarding or limitations in each of the three sports categories below.*** ( ___check here if you are using a brace.)

**Strenuous Sport**
(soccer, football, basketball, volleyball)
*check one box:*
- 100 ☐ no problems
- ☐ moderate problems during or after game
- ☐ severe problems; cannot participate

**Moderate Sport**
(tennis, racquetball)
*check one box:*
- 80 ☐ no problems
- ☐ moderate problems during or after game
- ☐ severe problems; cannot participate

**Light Sport**
(golf, bowling, hiking)
*check one box:*
- 60 ☐ no problems
- 50 ☐ moderate problems during or after game
- 30 ☐ severe problems; cannot participate

*Total Points* _________

**SPORTS ACTIVITY AND FUNCTION FORM** — **CINCINNATI KNEE RATING SYSTEM (F07A)**

## Appendix I: Injury-Psychological Readiness to Return to Sport Scale

**INJURY-PSYCHOLOGICAL READINESS TO RETURN TO SPORT SCALE**

Please rate your confidence to return to your sport on a scale from 0 – 100.

0 = no confidence at all

50 = moderate confidence

100 = complete confidence

1. My overall confidence to play is _____________

2. My confidence to play without pain is ____________

3. My confidence to give 100% effort is ____________

4. My confidence to not concentrate on the injury is ______

5. My confidence in the injured body part to handle the demands of the situation is _________

6. My confidence in my skill level/ability is __________

Add total and divide by 10 = _____

## Appendix J: Baseline Data for Hop Tests (Raw Scores)

| | Injured (cm) Mean SD | Uninjured (cm) Mean SD | Limb Symmetry Index (%) # Mean SD | Control (cm) Mean SD |
|---|---|---|---|---|
| **Single Hop for Distance** | 118.8<br>33.6 | 126.0 *<br>30.7 | 93.6<br>8.9 | 130.9<br>26.7 |
| **Triple Hop for Distance** | 380.5<br>98.1 | 395.4 *<br>87.1 | 95.7<br>7.7 | 423.4<br>89.2 |
| **Crossover Hop for Distance** | 334.6<br>97.6 | 349.1 *<br>78.9 | 94.9<br>10.6 | 378.0<br>86.4 |
| **Side Hop (Repetitions)** | 22.9<br>11.0 | 25.2 *<br>9.1 | 88.7<br>18.8 | 31.2<br>13.0 |
| **Vertical Jump** | 15.9<br>7.4 | 16.0<br>5.8 | 102.9<br>39.2 | 18.4<br>8.9 |

*Note.* *$p < 0.05$ between the injured and uninjured legs; # Limb Symmetry Index: the ratio of the involved to uninvolved limbs multiplied by 100.