Neuromuscular control and physical performance following anterior cruciate ligament reconstruction using a semitendinosus/gracilis double-strand graft: are there different levels of coping?

A dissertation prepared by Elsje de Villiers (DVLELS001) in partial fulfilment of the requirements for the Master of Philosophy degree in Sports Physiotherapy (MPhil Sports Physiotherapy) from the University of Cape Town

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(Date)
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<td>ACL</td>
<td>Anterior Cruciate Ligament</td>
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<td>ACLD</td>
<td>Anterior Cruciate Ligament Deficient</td>
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<td>ACLR</td>
<td>Anterior Cruciate Ligament Reconstructed (individuals/group)</td>
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<td>ADL</td>
<td>Activities of Daily Living</td>
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<td>ASIS</td>
<td>Anterior Superior Iliac Spine</td>
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<td>BF</td>
<td>Biceps Femoris</td>
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<td>BPTB</td>
<td>Bone-patellar tendon-bone (graft)</td>
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<td>CKRS</td>
<td>Cincinnati Knee Rating System</td>
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<td>CKRS - SAF</td>
<td>Cincinnati Knee Rating Scale – Sports Activity and Function</td>
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<td>EMG</td>
<td>Electromyography</td>
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<td>GRA</td>
<td>Gracilis (muscle)</td>
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<td>IKDC</td>
<td>International Knee Documentation Committee</td>
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<td>KOS</td>
<td>Knee Outcome Survey</td>
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<td>KOS - ADLS</td>
<td>Knee Outcome Survey - Activities of Daily Living Scale</td>
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<td>LG</td>
<td>Lateral Gastrocnemius</td>
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<td>LTV</td>
<td>Lean Thigh Volume</td>
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<td>MG</td>
<td>Medial Gastrocnemius</td>
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<td>MRI</td>
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<td>MVC</td>
<td>Maximum Voluntary Contraction</td>
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<td>MVIC</td>
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<td>RCT</td>
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<td>Rectus Femoris</td>
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Abstract

Background
The anterior cruciate ligament (ACL) is one of the primary stabilising ligaments of the knee joint and prevents anterior translation of the tibia in relation to the femur. There are three types of mechanoreceptors within the ACL which provide information about proprioception to the central nervous system, and play a role in dynamic joint stability. The ligament is commonly injured during sporting activities that involve jumping, twisting and turning. An ACL injury leads to a decrease in strength, proprioception and an alteration in movement patterns in the lower limbs.

ACL-reconstruction is indicated in cases where individuals have recurrent problems with episodes of giving way, pain and swelling. The two most popular autograft used in ACL-reconstruction are the bone-patellar tendon-bone graft and the semitendinosus/gracilis graft.

Recent studies proposed that two distinct groups of responders can be identified following ACL injury. ‘Copers’ were able to return to a relatively high level of function after their injury without episodes of giving way or instability of the knee joint. Individuals who were unable to return to their pre-injury level of sport participation or activity due to repeated episodes of giving way of their knee joint after ACL injury were classified as ‘non-copers’. Failure to recognise the differences between copers and non-copers, and how they respond following injury, could account for the inconsistencies in outcome measures described in the literature in the past, where most studies tended to
group all subjects with ACL injury together when studying different outcome measures. The underlying neuromuscular mechanisms for these differences in functional outcome following ACL-injury have not yet been identified. Furthermore, it has not been established whether individuals can also be classified as copers or non-copers following ACL-reconstruction and if these inherent differences in functional ability after ACL injury affect the outcome measures following surgery.

Objective

The objectives of this study were to (i) compare ACL-reconstructed individuals to a normal, healthy control group to assess whether there are any differences in self-reported function, muscle strength or functional outcome measures, and (ii) separate individuals who had undergone ACL reconstruction into specific ‘coper’ or ‘non-coper’ groups according to self-reported function. These identified groups were then correlated with outcome measures, particularly the neuromuscular performance during different strength and functional tests, to identify any potential neuromuscular mechanism responsible for the difference in functional outcome following ACL-reconstruction.

Methods

Seventeen subjects, who had undergone previous ACL-reconstruction using a double-strand semitendinosus/gracilis autograft, were studied at a minimum of 24 months following surgery. Nine males and eight females (mean age 29.9 ± 9.5 years) participated in this study. Isometric and isokinetic strength (concentric at 60° and 180°/s, and eccentric at 60°/s) of the quadriceps and hamstring muscles were tested in both injured
and non-injured limbs using a Biodex dynamometer. Each subject then performed a step up/down test, and four hop tests, bilaterally, during a single testing session. Electromyographic data was collected with surface electrodes from four muscles (vastus medialis, vastus lateralis, semitendinosus and biceps femoris) during the isokinetic strength testing and the functional step up/down test. EMG data was normalised to the mean amplitude of three maximum voluntary contractions measured during isometric strength testing.

Each subject completed three subjective questionnaires regarding their present symptoms and sporting activities; the Knee Outcome Survey - Activities of Daily Living Scale (KOS-ADLS), a Global Rating Score (GRS) and the Cincinnati Knee Rating Scale - Sports Activities Scale (CKRS - CSAS).

Ten age and gender matched controls (mean age 30 ± 7.3 years) were recruited as there is evidence to suggest that an ACL-injury can lead to bilateral adaptations. Group differences between the ACL-reconstructed and control groups were determined using independent t-tests.

In the second part of the study the subjects who had undergone ACL-reconstruction were classified as copers or non-copers according to four criteria based on timed hop test score, two self-reported knee function scores and number of episodes of giving way. These two groups were then compared for strength, functional hop tests and EMG data. Group differences were determined using independent t-tests.
Results

The control group scored significantly higher for the self-reported measures of function (KOS-ADLS and CKRS-SAS) compared to the ACL-reconstruction group. However, there were no significant differences for isokinetic quadriceps and hamstring muscle strength, functional hop tests and EMG measures of muscle activity in the VMO, VL, ST and BF muscles between the ACL-reconstructed and control groups. The time to reach peak torque for the hamstring muscle of the involved limb during the concentric strength testing at $180^\circ/s$ was significantly faster in the ACL-reconstructed group compared to the control group. The time needed to reach peak torque of the hamstring muscle of the involved limb during eccentric testing at $60^\circ/s$ was significantly slower in the ACL-reconstructed group compared to the control group.

In the second part of the study seven ACL-reconstructed subjects were classified as copers while ten ACL-reconstructed subjects were classified as non-copers. The copers scored significantly higher in the self-reported measures of knee function, the KOS-ADLS and GRS. However, there were no significant differences for isokinetic quadriceps and hamstring muscle strength, functional hop tests and EMG measures of muscle activity in the VMO, VL, ST and BF muscles between the involved and uninvolved limb of the coper and non-coper groups.

Conclusion

There were no differences in strength, functional hop tests or EMG activity between the ACL-reconstructed group and control group. This suggests that for these neuromuscular
outcome measures, ACL-reconstruction using a double-strand semitendinosis/gracilis graft delivers satisfactory outcome comparable to that of normal age and sport-matched individuals. The significant difference in time to reach peak torque for the hamstring muscle between the limbs of the ACL-reconstructed and control groups that was found in the present study may be a 'protective' mechanism or at least an alteration caused by the injury.

Copers and non-copers demonstrated no significant differences in strength, functional ability and EMG activity. This suggests that the differences in self-reported measures of knee function between the two groups can not be explained by the neuromuscular and physical outcome measures assessed in the present study. It is possible that the dissociation between self-reported functional capacity and physical performance between the coper and non-coper groups could be explained by the psychological profile of these individuals.

Key words

ACL-reconstruction; neuromuscular performance; muscle strength; hamstring graft
Chapter 1

Introduction and scope of the thesis

A torn anterior cruciate ligament (ACL) is one of the most disabling sports injuries an athlete can sustain, with a high incidence of complete non-return to sport or return to sport at a reduced level, often despite having reconstructive surgery (Wojtys & Huston 2000). ACL injuries are perhaps one of the most widely researched injuries in the orthopaedic and sport science fields. The ACL is one of the primary static stabilisers of the knee joint and consists of two parts. The anterior-medial band of the ACL prevents anterior translation of the tibia in relation to the femur, while the posterior-lateral band of the ACL is responsible for rotational stability (Woo et al. 1994; Norkin & Levangie 1992; Arnoczky et al. 1993). The ACL contains mechanoreceptors that play a role in the protective proprioceptive feedback mechanism of the knee, which contributes to the dynamic stability of the knee joint (Schutte et al. 1987; Schultz et al. 1984; St Clair Gibson 2002). The normal anatomy of the ACL bony attachments have been extensively investigated in the past, since meticulously restoring these precise ‘anatomical positions’ during reconstructive surgery (Arnoczky et al. 1993; Zarns & Adams 1988) is considered to be an important component of restoring optimal functional capacity to a patient with an ACL injury.

The two most commonly used grafts in ACL-reconstruction are the bone-patellar tendon-bone (BPTB) graft and semitendinosus/gracilis (SG) autograft. Both these techniques have been extensively investigated, comparing (i) the long-term outcome of each graft
with outcomes such as isokinetic strength, range of motion (ROM), laxity and instability, or (ii) the outcomes of the two kinds of grafts relative to each other. Previously, subjects following ACL-reconstruction were all grouped together, or groups were created based on the type of graft the patient had, to investigate strength, stability or functional outcome.

Previous research following ACL-reconstruction has focused on measuring different outcomes following surgery, such as isokinetic strength, range of motion, laxity and instability\(^1\) (Arvidsson et al. 1981; Seto et al. 1988; Natri et al. 1996; Shelbourne & Gray 1997; Osteras et al. 1998; Beard et al. 2001; Goradia & Grana 2001; Keays et al. 2003; Beynon et al. 2002; Nakamura et al. 2002; Feller & Webster 2003). Physical outcome measures, such as joint laxity and isokinetic muscle strength, have been shown to have a weak or insignificant relationship to functional outcome measures in both individuals with ACL-injury and following ACL reconstruction (Clark 2001; Keays et al. 2001; Eastlack et al. 1999; Snyder-Mackler et al. 1997).

Researchers have begun to recognize that individuals may respond differently following ACL injury and proposed that two distinct groups can be identified. Individuals who were able to return to a high level of function (Level I sports, at least weekly) after their injury without episodes of giving way or instability were classified as ‘copers’. On the other hand ‘non-copers’ were unable to return to their pre-injury level of sport participation or

\(^{1}\) In the literature laxity and instability seem to be used interchangeably. In the present study laxity will refer to the ligament (ACL) and is measured by an increased anterior tibial translation (in mm) as measured by a knee ligament arthrometer (KT-1000), while instability refers to the lack of stability at a joint, of which ligament laxity is only one of the underlying factors.
activity due to repeated episodes of giving way (Eastlack et al. 1999). Failure to recognise the differences between copers and non-copers, and how they respond following injury, could account for the inconsistencies or lack of results found in the literature in the past where most studies tended to group all subjects following ACL injury together.

It has not yet been determined whether individual differences in the ability to dynamically stabilise their knee may also affect a subject’s outcome following ACL-reconstruction. In one study attempting to identify factors that may predict residual quadriceps weakness following ACL-reconstruction, the authors found that pre-operative EMG deficit of the quadriceps muscle was the best predictor of functional performance (hop test) at 6 months follow-up (McHugh et al. 2002). This may indicate that neuromuscular deficits pre-operatively could result in reduced or poorer functional outcome following reconstruction, and create a non-coper.

Objective measures of ligament stability or muscle strength following ACL-reconstruction does not appear to correlate well with functional outcome (Kocher et al. 2004; Seto et al. 1988). What then does determine satisfactory outcome following ACL-reconstruction? This is an important question to help focus future research on how to go about improving the functional outcome following expensive ACL-reconstruction and time-consuming rehabilitation, and ultimately ensure the speedy, successful return of athletes to their previous level of function.
This study aimed to determine what factors contribute to a successful outcome following ACL-reconstruction by (i) comparing ACL-reconstructed individuals to a normal, healthy control group to assess whether there are any differences in self-reported function, muscle strength and functional outcome measures between the groups, and (ii) separating individuals who had undergone ACL reconstruction into specific 'coper' or 'non-coper' groups according to self-reported function, and then correlating these groups identified with various neuromuscular outcomes to assess whether there are any significant differences in neuromuscular function between the identified groups.
Chapter 2

Review of the anterior cruciate ligament
– normal, injured and reconstructed states
2.1 Introduction

The ACL is one of the primary stabilising ligaments of the knee joint. It plays a major role in providing stability during functional and sporting activities. ACL injuries are one of the most common knee injuries in sport and a potential career-ending injury for an athlete. After an athlete sustains an ACL tear he or she is faced with difficult choices and often contradictory advice regarding surgical or conservative treatment and rehabilitation; how long to wait before having surgery; when to return to sporting activities; the likelihood of recurrence and the long-term implications of the injury/surgery.

There is a vast amount of often contradictory information in the literature and continuously changing concepts regarding ACL rehabilitation, and it is therefore difficult for the clinician to keep up to date and to be able to provide the patient with an informed choice about their treatment and rehabilitation options. There is pressure on the clinician regarding issues such as return to sport, prevention of recurrence, and being familiar with current concepts essential to decision making, not only regarding high-income professional sportsmen and women but for every active individual who is eager to return to their full sporting potential.

2.2 Epidemiology of injury

ACL injuries are common in sport that involves twisting, turning, cutting and jumping. It is a common injury in skiing (Williams et al. 1995), soccer (Micheli et al. 1999; Agel et al. 2005), basketball (Zelisko et al. 1982), volleyball (Ferretti et al. 1992) and netball (Hopper & Elliott 1993) (Table 2.1).
Table 2.1. Summary of the incidence of ACL injuries in sporting populations

<table>
<thead>
<tr>
<th>Study name</th>
<th>Sport Investigated</th>
<th>Type of study</th>
<th>Population during seasons</th>
<th>Investigation</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zelisko et al (1982)</td>
<td>Professional basketball players</td>
<td>Retrospective study</td>
<td>Season 1: n = 13; Season 2: n = 15</td>
<td>Comparing injuries between men and women over 2 consecutive seasons</td>
<td>Total injuries: ♂ = 134; ♀ = 138; Knee (% of total injuries): ♂ = 22 (16.4%); ♀ = 17 (12.3%)</td>
</tr>
<tr>
<td>Ferretti et al (1992)</td>
<td>Volleyball</td>
<td>Prospective study</td>
<td>n = 52</td>
<td>* in 48 of the 52 cases, injury occurred during a phase of jumping</td>
<td>42/52 (81%) were ♂ (4x more injuries in females than males)</td>
</tr>
<tr>
<td>Williams et al (1995)</td>
<td>Skiing</td>
<td>Prospective study</td>
<td>n = 55 (men and women)</td>
<td>Initial questionnaire with details of - country of accident - treatment before return - mode of referral - delay between injury and return - type and site of injury</td>
<td>UL = 35 (59.3%); LL = 22 (37.3%); Trunk &amp; spine = 2 (3.4%); ♂ = 30; ♀ = 25; Total knee injuries = 13 (22%); one person had to have an ACL repair</td>
</tr>
<tr>
<td>Hopper et al (1993)</td>
<td>Netball players at the 1988</td>
<td>Retrospective (questionnaire) and prospective</td>
<td>n = 228</td>
<td>Completed questionnaires and were assessed for injury status</td>
<td>52 out of 228 players sustained back and lower limb injuries (22.8%); 2 players were diagnosed with an ACL injury during the tournament (3.8%)</td>
</tr>
<tr>
<td></td>
<td>Australian Netball Championship</td>
<td></td>
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<tr>
<td></td>
<td>basketball players from 1990 to 2002</td>
<td></td>
<td></td>
<td></td>
<td>69 soccer injuries (♀: 20); 40 basketball injuries (♂: 11); Overall: girls at least 2x more injuries</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Micheli et al (1999)</td>
<td>Adolescent soccer and</td>
<td>Retrospective study</td>
<td>n = 109 (78 girls, 31 boys)</td>
<td>Review of 13 to 19-year old adolescent athletes admitted for ACL reconstruction due to soccer or basketball injuries</td>
<td>4.2 injuries per 100,000 skier-days in men; 4.4 injuries per 100,000 skier-days in women; Incidence of ACL injuries between male and female professional alpine skier are similar</td>
</tr>
<tr>
<td></td>
<td>basketball players</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viola et al (1999)</td>
<td>Professional alpine skiers</td>
<td>Retrospective review</td>
<td>n = 7155 (4537 men and 2618 women)</td>
<td>Initial screening before each ski season. ACL injured professional alpine skiers were identified through mandatory workers’ compensation claims and re-evaluated.</td>
<td></td>
</tr>
</tbody>
</table>

UL = upper limb; LL = lower limb
In skiing injury rates of between 4.2 and 4.4 injuries per 100,000 skier-days for men and women professional skiers have been described (Wojtys et al. 2002). Both Micheli et al (1999) and Agel et al (2005) reported that female soccer players are two times more likely to sustain an ACL-injury than sport-activity matched males. Zelisko et al (1982) studied injury patterns in basketball players and found that female players sustained significantly more knee and thigh injuries than their male counterparts, however the authors did not separate ACL injuries from other knee injuries. Ferretti et al (1992) reported that that female volleyball players were four times more likely to sustain an ACL-injury than their male counterparts. Hopper and Elliott (1993) found two players sustained ACL injuries during the 1988 Australian netball championships (n = 228), this was 3.8% of the total injuries (n = 52) sustained during the tournament. The study did not report the total number of playing days during the championship.

The risk factors that can lead to ACL injuries can be divided into extrinsic and intrinsic factors. Extrinsic factors (forces outside of the body that can cause injuries) include competition level, position of play, playing surface, footwear, orthotics and equipment (Murphy et al. 2003; Dugan 2005). Intrinsic factors (factors from within the body) include age, gender, hormone levels, ligament laxity, previous injury, aerobic fitness, body anthropometry, limb dominance, flexibility, muscle strength and imbalance, muscle reaction time, postural stability, anatomic alignment and foot biomechanics (Murphy et al. 2003; Dugan 2005).

Women have a two to six times greater risk of sustaining an ACL injury (Leiphart et al. 2002; Hewett et al. 2005b; Agel et al. 2005). Several causative factors for this
phenomenon have been investigated and will be discussed later. However, in 1999 the National Institutes of Health/American Academy of Orthopaedic Surgeons-sponsored consensus conference on this issue (ACL injuries in females) concluded that the most likely risk factors for ACL injuries in females are biomechanical and neuromuscular factors (Lephart et al. 2002).

2.3 An overview of the anterior cruciate ligament

2.3.1 Anatomy of the knee and ACL

The knee joint, like several other joints in the body, has a dual role: firstly it must produce mobility during movement of the lower limb, to help propel the body and clear the ground, and secondly it must supply stability for the supporting limb during weight-bearing activities, such as dynamic control during the stance phase of gait or static control during standing (Norkin & Levangie 1992).

The knee is a hinge joint that consists of two distinct articulating parts\(^2\): the tibio-femoral joint and the patello-femoral joint\(^3\). The tibio-femoral joint is formed by the large medial and lateral condyles of the distal femur and the shallow medial and lateral tibial condyles or plateaus of the proximal tibia, and it acts as the main weight-bearing joint. The primary movements of the knee are flexion-extension in the sagittal plane, while the secondary motions of medial-lateral rotation takes place in the transverse plane. Due to the incongruence of the femoral and tibial surfaces, flexion and extension is combined

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\(^2\) The tibiofibular joint forms the third part of the knee complex, however since it is not a weight-bearing joint, the tibiofibular joint will not be discussed in the present study.

\(^3\) The patello-femoral joint (PFJ) is formed by the posterior surface of the patella and the anterior surface of the femoral condyles. Although intricately related to biomechanics of the knee joint, the PFJ will not be discussed in the present study.
with the accessory motions of rolling and gliding to maintain contact between the articulating surfaces. The accessory motion of rotation is also intricately linked to the locking-unlocking mechanism of the knee in terminal extension (Norkin & Levangie 1992).

The knee joint is dependent on several structures for stability. The capsule, various ligaments around the knee and the menisci act as static (primary) stabilisers, while the muscles and tendons around the joint act as dynamic (secondary) stabilisers. The medial and lateral collateral ligaments, with their close relation to the medial and lateral menisci, help maintain medial and lateral integrity of the knee joint. The medial and lateral menisci are fibrocartilaginous discs that enhance the congruency between the femoral condyles and tibial plateau and play a role in shock absorption (Norkin & Levangie 1992).

The ACL contributes to the stability of the knee joint to a different extent in various degrees of flexion and extension, and prevents hyperextension of the knee (Liu-Ambrose 2003). The ACL consists of numerous fascicles that are grouped into two bundles: an anterior-medial and posterior-lateral part. Both bundles originate from the posterior aspect of the medial surface of the lateral femoral condyle and insert into the anterior-medial aspect of the tibial surface (Woo et al. 1994; Arnoczky et al. 1993). The main function of the anterior-medial band is to prevent anterior translation of the tibia in relation to the femur while the posterior-lateral band is responsible for rotational stability.
Several types of sensory nerve endings within the ACL provide afferent information to the central nervous system. Three types of mechanoreceptors\(^4\), as well as free nerve-endings have been identified: two types of Ruffini endings, and Pacinian corpuscles. The mechanoreceptors play a role in providing information about the speed, acceleration and direction of motion, as well as proprioceptive information about the position of the joint to the central nervous system. The free nerve-endings are responsible for afferent pain signals (Arnoczky et al. 1993; Schutte et al. 1987; Schultz et al. 1984). Mechanoreceptors also influence gamma motor neuron activation, which is responsible for setting muscle stiffness. Muscle stiffness has been shown to enhance dynamic joint stability (Riemann & Lephart 2002a).

2.3.2 Functional anatomy of the muscles acting around the knee joint
The main muscles that act on the knee are the quadriceps, the hamstrings and the gastrocnemius muscles. The hamstrings, which consist of the semimembranosus and the semitendinosis medially and the biceps femoris laterally act as knee flexors, together with the medial and lateral heads of the gastrocnemius. The quadriceps muscle consists of the rectus femoris, vastus medialis, vastus intermedius and the vastus lateralis and act as extensors of the knee joint.

2.3.3 Neuromuscular control around the knee joint
Kalund et al (1990) defined neuromuscular control as the unconscious response to afferent signals which affects dynamic knee joint stability. Riemann et al (2002b) defined

\(^4\) Mechanoreceptors act as transducers; converting physical stimuli into specific neural signals, which can then be transported to the central nervous system.
neuromuscular control as 'the unconscious activation of dynamic restraints occurring in preparation for and in response to joint motion and loading for the purpose of maintaining and restoring functional joint stability'. Neuromuscular control of the knee joint has been extensively studied. The outcome measures used to measure neuromuscular control are varied and include time-to-peak torque (ms) and muscle reaction time (ms) (Wojtys & Huston 2000), threshold for detecting passive motion (Ageberg 2002), muscle strength (Wojtys & Huston 2000; Noyes et al. 1991; St Clair Gibson et al. 2000a) functional performance (various hop tests), and EMG measurements of movement and activation patterns (Solomonow et al. 1987; Kalund et al. 1990; Devita et al. 1997).

The ACL contains mechanoreceptors that provide information about the speed, acceleration and direction of motion, as well as proprioceptive information about the position of the joint to the central nervous system (Arnoczky et al. 1993; Schutte et al. 1987; Schultz et al. 1984). Experimental tests have revealed that when the ACL is stressed directly, the mechanoreceptors initiate a moderate inhibitory effect of the quadriceps while directly stimulating the hamstrings to contract (Solomonow et al. 1987).

The authors concluded that these results provide evidence that a direct reflex arc exists between the ACL and hamstring muscles, indicating that the hamstring acts as agonists to the ACL in resisting anterior joint displacement. Thus the ACL plays an important role in functional stability of the knee by means of the sensory information from its mechanoreceptors.
2.3.4 Mechanisms of injury

The epidemiology of injury has been discussed previously. However, the mechanisms of ACL injury are another topic that has also been extensively researched. ACL injuries are common in pivoting and jumping sports. Several mechanisms have been described that lead to ACL injuries. Direct forces include a force applied to the knee while the foot is planted, or an anteriorly directed force while the knee is flexed. However, most ACL injuries occur during non-contact episodes (Zarins & Adams 1988). Daniel et al (1985) studied 138 patients with traumatic knee injuries within two weeks of the onset of injury. Seventy-five of the subjects underwent arthroscopy, of which 53 were diagnosed with a complete ACL tear (38.4% of the total). Seventy percent of the total injuries (96/138) were sustained during sport activities. The majority of these sporting injuries did not involve direct contact. Indirect forces included jumping and landing with a straight leg (hyperextension injury) or with increased valgus motion; or a medial rotational force when the athlete pivots on the leg to change direction. However, the authors did not report how many of the ACL injuries resulted from sporting activities. Recent research has shown that the ACL ligament is at most risk of injury during ground contact when landing from a jump, when coupled with an awkward body position (Lephart et al. 2002; Zarins & Adams 1988).

As described previously, female athletes have a significantly increased risk in sustaining an ACL injury (Hewett et al. 2005b). Hewett (2000) described the three most likely etiological factors responsible for this increased rate amongst females: anatomical, hormonal and neuromuscular. Current consensus seems to be that neuromuscular factors are the most likely mechanism underlying this increased risk (Hewett 2000). It is also the
one factor where training or physiotherapy input can have an effect (Lephart et al. 2002; Hewett et al. 2005a). A cross-sectional controlled laboratory study examined the three-dimensional kinematic data of 181 pre-adolescent and adolescent athletes (81 males and 100 females) to assess the dynamic control of the knee joint during a vertical drop jump (Hewett et al. 2004). The study found that when tested following the pubertal growth spurt, female athletes land with increased valgus motion of the knee compared to their male counterparts. This indicates that the musculoskeletal changes that accompany growth may lead to decreased dynamic stability around the knee of adolescent female athletes.5

Hewett et al (2005b) attempted to identify whether it is possible to identify athletes who are at an increased risk of ACL injury. This prospective study followed 205 female athletes participating in high-risk sports (soccer, basketball and volleyball) over 2 sport seasons. Three-dimensional kinetic and kinematic data were collected from a drop vertical jump and the flexion-extension and abduction-adduction moments for each subject were documented. A total of nine ACL injuries were recorded during the following season, all from indirect/non-contact injuries. The researchers found significant differences in the knee abduction angles between ACL-injured and non-injured subjects. The knee abduction angle during landing was on average 8° greater in the ACL-injured than in the uninjured athletes. No differences in knee flexion angles at initial contact or peak knee flexion moments were found between ACL-injured and non-injured subjects.

5 When looking at injuries that occur in and around the knee joint, one cannot consider the joint in isolation. It is important to view the knee as part of a dynamic chain (proximally the spine, pelvis and hip and distally the ankle and foot) and keep in mind the main function of the lower limb, i.e. stability during static postures and mobility during static postures and mobility during gait. Reviewing other factors that may lead to ACL injuries (e.g. podiatric biomechanical factors, core stability) are beyond the scope of this review.
The study concluded that the increase in knee valgus angles and moments found in injured athletes seem to be the main predictive factors for increased risk of ACL injury. Future research should concentrate on how to identify these risk factors during screening examination of athletes since three-dimensional investigation of all individuals at risk are neither financially appropriate nor practical.

2.3.5 Prevention of injuries

There is evidence in the literature that neuromuscular training has the potential to improve single-limb postural stability in female athletes (Paterno et al. 2004) and decrease the incidence of ACL injuries in female athletes (Lephart et al. 2002). A recent systematic review of the literature concurred with these studies and concluded that preventative neuromuscular training programs decreased the risk of ACL-injuries in females by decreasing peak landing forces, reducing valgus and varus moments at the knee, improving the hamstring peak torque and increasing jump height (Hewett et al. 2005a). With changes in neuromuscular control around the knee coinciding with the growth spurt during puberty, special attention should be given to preventative strategies and exercises within the training programs of adolescent athletes, especially females. Coaches and other individuals involved in these young individuals should be made aware of the benefit of incorporating neuromuscular training into regular exercise regimes.

2.4 The ACL deficient knee

After an ACL injury the ACL-deficient (ACLD) individual can experience several symptoms, of which instability and ‘giving way’ of the joint during functional activities are the most disabling. Noyes et al (1984) suggested that a complete tear of the ACL can
initiate a cascade of symptoms that is marked by continued functional disability (the 'anterior cruciate insufficient knee syndrome'), the level of which is dependent on the activity level of a person. Repeated episodes of giving way or subluxation can also lead to secondary meniscal tears and accelerated joint degeneration (Zarins & Adams 1988).

2.4.1 Muscle strength in ACL-deficient subjects

Several studies show a decrease in concentric (Wojtys & Huston 2000; Noyes et al. 1991; St Clair Gibson et al. 2000a) and eccentric (St Clair Gibson et al. 2000a) quadriceps peak torque value in ACL-deficient (ACLD) subjects. Hamstring peak torque shows a smaller, less significant decrease in strength (Wojtys & Huston 2000; Noyes et al. 1991; St Clair Gibson et al. 2000a). This may be due to the fact that the hamstrings, as agonist to the ACL, play an important role as a joint stabiliser in the ACLD knee (Solomonow et al. 1987).

A study by Konishi et al (2003) on gamma-loop dysfunction demonstrated that ACL-injury and the subsequent reduced afferent input leads to reduced maximum muscle strength in the contra-lateral leg. The authors concluded that,

'because the strength of the quadriceps femoris muscle on the uninjured side in patients with unilateral ACL rupture is usually used as a reference to evaluate muscle weakness in clinical situation, the strength reduction present in the quadriceps femoris muscle of the uninjured side could lead to an underestimation of muscle weakness'.
Therefore, studies which use the uninjured limb as control could lead to erroneous conclusions based on the above finding. To control for this potential underestimation of muscle weakness a study should therefore include a separate control group.

2.4.2 Function of the ACL-deficient knee

Several studies have shown that ligament laxity or increased anterior tibial translation is not related to functional outcome following ACL injury (Eastlack et al. 1999; Snyder-Mackler et al. 1997). Snyder-Mackler et al. (1997) recognised an inherent difference in the functional stabilising capabilities in patients following an ACL injury. They divided their subjects into two groups. In the first group all the subjects returned to their previous sporting activities, and were called ‘copers’. In the second group, the subjects did not improve with conservative management and rehabilitation, and required surgical intervention. This group was called ‘non-copers’. Despite there being no significant difference in laxity measures between the two groups, this was one of the first studies to suggest this inherent difference in dynamic stability between ACLD individuals and divide subjects into separate groups according to their functional ability. Failure to recognise the differences between copers and non-copers, and how they respond following injury, could account for the inconsistencies found in the literature in the past where most studies tended to group all subjects with ACL injury together.

Eastlack et al (1999) later refined their definition of the two identified groups. They called the group who compensated well for ACL injury ‘copers’: ‘A small percentage of
ACL-deficient subjects [who] are able to return to function at a high level (Level I sport\(^6\), at least weekly) after injury without complaint of instability'. The term ‘copers’ was first used in a study by Daniel et al (1994). They found that 147 of 236 subjects who were ‘KT unstable’ (more than 3mm side-to-side difference in anterior displacement difference when tested with KT 1000 arthrometer) were capable of coping with their injuries without reconstructive surgery. ‘Non-copers’ were re-classified by Eastlack et al (1999) as those individuals ‘who are unable to return to their pre-morbid level of sports play or activity because of repeated episodes of giving way’ of their ACLD knee joint. In their study, in which they compare laxity, instability and functional outcome following ACL injury, Eastlack et al (1999) concluded that the measurement of ACL ligament laxity did not predict the functional outcome (whether an individual was a coper or non-coper)\(^7\). The study identified four variables that can distinguish copers from non-copers: copers demonstrated greater quadriceps strength, hop testing, global rating of function and self-reporting of function scores than non-copers (Eastlack et al. 1999). The reported sensitivity of the combined tests was 97% and the specificity was 92%. These were the first objective variables identified in the literature to help identify an individual as a coper or non-coper.

In a longitudinal study on functional recovery following ACL injury, Button et al (2006) found that only 5% of individuals who participated in high level activities before their

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\(^6\) Level I sport is defined as sporting activities that include jumping, pivoting and cutting (basketball, football, soccer) (Daniel et al. 1994).

\(^7\) Eastlack et al (1999) also identified another group of individuals who they called ‘adapters’. The authors commented that this group represents the vast majority of ACL-deficient individuals: those people who are able to manage without reconstructive surgery and avoid episodes of pain and giving way by adjusting their activity levels (i.e. they do not return to their previous levels of sport or they led mainly sedentary lifestyles anyway before the injury).
injuries were able to return to them (n = 63). They identified that gait variables and activity levels before injury were the most useful variables for distinguishing between copers, adapters and non-copers.

In a study by Rudolph et al (1998) the subjective self-rating score (measured as percentage compared to the knee function prior to injury) of non-copers was significantly lower than that of the copers. The non-copers scored the function of their involved knee at 53.6% (9.4%) while the copers scored their involved knee function at 92% (± 8.4%) (t=8.259, p=0.000). However, the knee ligament laxity values, as measured by KT-2000 arthrometer, of the copers and non-copers were the same.

There have been various theories proposed about what mechanisms determine an individual’s knee stabilising abilities following an ACL-injury. Zarins et al (1988) concluded from their review of the literature that anatomical factors such as the contour of the bones, the capsule, the collateral ligaments and the menisci determined the level of instability a person may suffer following ACL-injury. Other studies have focussed on the role of dynamic stability, as a function of neuromuscular control, around the knee following ACL injury (Solomonow et al. 1987; Sjölander et al. 2002).

2.4.3 Neuromuscular control of the ACL deficient knee

As described previously, the ACL plays an important role in the neuromuscular control of the knee joint via the sensory information from its mechanoreceptors. A study by Solomonow et al (1987) provided evidence from animal experiments that a direct reflex arc exists between the ACL and hamstring muscles, indicating that the hamstring acts as
an agonist to the ACL in resisting anterior joint displacement. The ACL, although one of the primary stabilisers of the knee, can not be the only structure responsible for functional stability of the knee joint, since several studies have indicated that joint laxity or increased anterior tibial translation is not related to functional outcome following ACL injury (Eastlack et al. 1999; Snyder-Mackler et al. 1997).

In a second part of the above study, Solomonow et al (1987) found that during a loaded extension test in a group of ACL-deficient individuals, subluxation of the knee occurred between 37° and 46° and coincided with an increase in hamstring muscle activity and simultaneous decrease in quadriceps muscle activity. These changes in muscle activity provide evidence for a second reflex arc mediated by the mechanoreceptors in the muscles or joint capsule around the knee joint (Solomonow et al. 1987). Although this reflex arc has a longer response time than the primary, fast-response reflex, Solomonow et al (1987) suggested that it contributes to the dynamic stability of the joint in the ACL-deficient individual. Another important observation that the authors made during this study is that they identified that two of the ACL-deficient subjects were able to participate in normal sport (both level I sport players) without any complaints of instability (i.e. possible copers). The authors concluded that in these cases the secondary reflex arc was sufficient to prevent episodes of instability and postulated that if the hamstring muscles were maximally rehabilitated, this would contribute to the efficacy of this reflex arc. This reflex may therefore be part of an underlying neuromuscular mechanism present in copers.
However, the existence of the protective nature of these ligament-muscle reflexes, such as described above, is theoretically questioned in a review of the literature by Sjölander et al (2002). The authors state that although the ligament-muscle reflexes have been described, there is no evidence that these reflexes actually protect the joint from injury in light of the fact that they are slow. The authors suggested that it is more likely that afferent sensory information from the mechanoreceptors of ligaments, and other joint structures, contribute to the continuous regulation of muscle activity through feedforward mechanisms. These feedforward mechanisms help increase functional joint stability by increasing muscle stiffness through a continuous reflex modulation of the γ-muscle spindle system.

Whatever the mechanism of neuromuscular control around the knee joint, following ACL-injury, whether it is due to pain and joint effusion or loss of mechanoreceptors of the ACL, there appears to be a decrease in this crucial protective mechanism. This is evident in an increase in episodes of giving way, and lower self-reported knee function in some ACL-deficient individuals (Snyder-Mackler et al. 1997; Rudolph et al. 1998; Eastlack et al. 1999).

2.4.4 Proprioception in ACL-deficient subjects

There is evidence in the literature that ACL-injury leads to the loss of proprioception

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8 According to Riemann and Lehpert (2002b) proprioception is one of the most misused terms when it comes to describing the functions of the sensorimotor system. It was originally used by Sherrington (as early as 1906) to refer to the 'afferent information arising from "proprioceptors" located in the "proprioceptive field"'. Thus, if proprioception is used as originally intended, it describes the afferent input from the peripheral joints and structures, which ultimately contributes to the regulation of posture and joint stability. However, as used in the literature it can mean anything from joint position sense, balance, somatosensation and reflexive joint stability. Since the term has been used interchangeably in the literature, it will be used as such in the present study when reporting on the literature, and not in its originally intended meaning.
which results in functional disability (Barrack et al. 1989; Beard et al. 1992). Corrigan et al (1992) reported a decrease in threshold for movement detection and position sense when comparing a group of ACL-deficient individuals to a control group. They also correlated proprioception with muscle balance and found that subjects who had greater hamstring to quadriceps isometric muscle strength ratio performed better in the proprioception tests. This reduced proprioception and muscle control after ACL injury could lead to changes in movement and activation patterns.

2.4.5 Movement patterns

In a study that assessed movement patterns following ACL injury, the subjects were divided into copers and non-copers (Rudolph et al. 1998). The copers in this study were similar to the group described by Eastlack et al (1999), having returned to all pre-injury activity without limitation, and reported one or less episodes of giving way since their injury. Rudolph et al (1998) included a self-rating score of the copers’s current level of knee function as 85% compared to their pre-injury levels of function. The authors suggested that the inconsistencies found in the literature in the past may be due to the failure to recognise the differences in the movement patterns between these two groups. The kinematic and kinetic differences found between the copers and non-copers were most noticeable during the early stance phase of walking and jogging, which is when body weight is being transferred onto and accepted by the involved limb. At initial contact of the involved limb the non-copers landed with significantly less flexion, using a characteristic ‘stiffening strategy’ to try and maintain knee stability. The main limitation of this study is that they did not compare the two groups with a control group, but used the uninvolved limb as control. In a follow-up study, Rudolph et al (2001) confirmed the
above movement pattern in non-copers, i.e. reduced knee flexion and reduced knee extensor moment, and also found that copers moved in a similar manner to uninjured individuals in a control group.

In a further study which investigated the walking patterns of ACLD individuals, subjects were divided into two groups (copers and non-copers), and also compared to a control group of healthy individuals (Alkjaer et al. 2003). They combined kinetic and kinematic information with EMG data from the vastus medialis, vastus lateralis, semitendinosus and biceps femoris muscles. The results of this study supported the findings of Rudolph et al (1998) that described that non-copers walk with a reduced knee extensor moment. This reduced knee extensor moment was not associated with decreased quadriceps EMG activity. Copers walked with greater knee flexion during the first half of stance phase, and the authors hypothesised that copers stabilise their knees by co-contraction of the quadriceps and hamstrings muscles.

The finding of Alkjaer's study does not support the findings of Berchuk et al (1990) who first described a 'quadriceps avoidance gait' in ACLD individuals. Berchuk et al (1990) found a reduced peak knee extensor moment in ACLD subjects in their study and hypothesised that this was due to decreased quadriceps activity to avoid excessive anterior tibial translation. However, the conclusion of this study was based on joint kinetics and did not include EMG investigation to verify their findings. Further studies are needed to investigate the variation in walking pattern following ACL injuries found in the literature.
2.4.6 Psychological response to ACL injuries

Nyland et al (2002) studied the perceived functional ability of patients following acute ACL injury (<1 month after onset). They found that patients with a higher perceived functional ability displayed a greater internal health locus of control\(^9\), as measured by the Health Locus of Control Scale (HLC). All the subjects in the study went on to have ACL reconstruction. These findings of the pre-operative health status beliefs were not correlated with any outcomes following ACL reconstruction. None of the studies on copers and non-copers (Eastlack et al. 1999; Lewek et al. 2003) investigated the role that psychological factors may play in an individual's functional ability or perceived functional ability following ACL injury.

Nyland et al (2002) postulate that addressing any external health locus of control a patient may perceive before surgery, by cognitive therapy strategies, could improve outcomes following surgery, and advocate further research on psychosocial attributes that could influence patient outcome.

2.4.7 Implications of ACL injuries

In summary it is evident from the above literature that an ACL injury can lead to significant changes in the functional ability of an individual. The ACLD individual, who is not a 'coper', has an increased risk of joint instability and episodes of giving way, which lead to joint effusion and pain. This increase in femoral motion can cause

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\(^9\) An internal health locus of control refers to an individual's belief that their outcome following injury or surgery is directly related to their own individual behaviour. An external health locus of control refers to the belief that one's outcome is under the control of others (e.g. doctor, physiotherapist) or is determined by fate, luck or chance (Nyland et al. 2002).
accelerated degenerative changes of the knee joint (Liu-Ambrose 2003). Furthermore, an ACL injury can lead to pathological laxity of the knee joint and changes in muscle function around the knee joint, which in turn could substantially reduce an athlete’s quantity and intensity of training (Doyle et al. 1998). It is important to take these changes in neuromuscular function into account when considering the most appropriate management approach in ACLD individuals.

2.5 Management of ACL injuries

2.5.1 Non-surgical

2.5.1.1 Indications for non-surgical treatment

Conservative treatment of the ACLD knee may be an appropriate choice in individuals who place only moderate physical demand on their knee (adapters) or in individuals with inherent dynamic knee stabilising strategies (copers). Fitzgerald et al (2000) developed a screening examination to help separate those individuals who had potential to succeed with non-surgical treatment from those patients who may be at risk of re-injury. To be classified as an individual with good potential to succeed from non-surgical management, a subject needs to meet the following criteria:

i. Timed hop test ≥ 80% compared to the uninjured limb;

ii. Knee Outcome Survey’s Activity of Daily Living Scale score of ≥ 80%;

iii. Global rating of knee function ≥ 60% compared to their pre-injury levels, and

iv. Number of episodes of giving way ≤ 1

These criteria were used to identify subjects who had good potential to succeed with active rehabilitation. The authors recommended that a patient be considered for surgical
reconstruction if they did not fulfil all of these criteria. Lewek et al (2003) used the screening examination described above to help categorise ACL-injured individuals as 'potential copers' or non-copers, based on the classification scheme of Eastlack et al (1999)\(^{10}\). They proposed that this screening examination be administered after an initial period of treatment to negate the effects of impairments associated with the acute injury e.g. pain, swelling, decreased ROM. There have been no studies that have investigated whether individuals could be classified as copers or non-copers following ACL-reconstruction and no screening examination has been developed or tested.

2.5.1.2 Rehabilitation of ACL-deficient individuals

Lewek et al (2003) also recommended that after an individual had been identified as a potential coper, they should undertake a further period of rehabilitation that included neuromuscular training. Only after returning to pre-injury levels of function, without any episodes of giving way, for a minimum of one year can a 'potential coper' be classified as a coper. The non-copers, who were identified, were sent for surgical intervention. Fitzgerald et al (2000) identified twenty-six individuals, with good potential to succeed with non-surgical management (i.e. copers), through their screening examination, and randomly assigned them to either a standard rehabilitation program or a standard program plus perturbation training\(^{11}\). At 6-month follow-up the authors reported that 69% of all

\(^{10}\) Eastlack et al (1999) initially separated individuals as copers or non-copers on a retrospective classification system: 'copers' were those ACLD-individuals who had returned to their previous level of activities for a minimum of one year, without any episodes of giving way.

\(^{11}\) The perturbation training program consisted of: (i) anteroposterior (AP) and mediolateral (ML) perturbations on a Balance Master motorized force platform (Neurocom International Inc, Clackamas, USA), (ii) AP and ML perturbations on a square tiltboard, (iii) multidirectional perturbations while the subject was standing with one leg on a roller board while the contralateral leg was supported on a stationary platform, and (iv) multidirectional perturbations while the subject was standing balancing on one leg on the roller board (Fitzgerald et al. 2000).
subjects successfully returned to full sporting activity - 50% of the standard rehabilitation program and 92% of the perturbation training group.

2.5.1.3 Outcome
From the above study it seems evident that, if correctly identified, individuals with inherent dynamic knee stabilising abilities are more likely to return to full sporting activities, without any recurrent episodes of giving way, if they undertake neuromuscular training, in the form of perturbation training, as part of their rehabilitation. However, this is the findings of a single study and further longitudinal studies with long-term follow-up are required to assess the success of this management strategy.

2.5.2 Surgical Management
The normal anatomy of the ACL bony attachments have been extensively researched in the past because of the benefits of restoring these precise ‘anatomical positions’ during reconstructive surgery (Arnoczky et al. 1993; Zarins & Adams 1988). By identifying and restoring this ideal graft position, the surgeon aims to reproduce the anatomy and function of a normal ACL (Fu et al. 1999).

2.5.2.1 Indications for surgery
Surgery has been suggested to be necessary when patients have repeated episodes of instability, effusion, pain and reduced function of the knee joint (Arvidsson et al. 1981). Noyes et al (1984) recommended surgical reconstruction for patients who had continuous disability and who were reluctant to alter their athletic activities, or in case of patients who continued to have symptoms and dysfunction in the course of their normal activities.
of daily living. The main indication for surgery is repeated episodes of giving way, which in the past were considered the start of a cascade of joint damage and swelling that resulted in further articular cartilage damage and a higher risk of osteoarthritis. Although surgery is more common in younger, active individuals who are less likely to adapt their lifestyles or sporting activities, Novak et al (1996) found that older individuals (over the age of 35) had good functional and objective outcomes following ACL-reconstruction, which were comparable to those of a younger patient population.

There has been some controversy regarding whether ACL-reconstruction should be performed in the acute (< 6 weeks following original injury) phase after injury, and whether the time period from injury to reconstruction affects outcome. Goradia et al (2001) compared the outcomes of ACL-reconstruction following acute ACL-reconstruction (within six weeks of injury) to chronic reconstruction (> six weeks from original injury). The authors concluded that following ACL-reconstruction using a semitendinosus/gracilis autograft, no significant differences for laxity, muscle strength, ROM or sport activity levels were found between the acute and chronic groups. Furthermore, at a 2 to 6 year follow-up, more than 90% of all patients were rated as having normal or nearly normal knees according to the International Knee Documentation Committee (IKDC) rating. Similar results were found in a study by Shelbourne et al (1997) where 89% of an acute ACL-reconstructed group (using PT autograft) were rated as having normal or nearly normal knees, while in the group that underwent ACL-reconstruction after three months (chronic group) 85% reported having normal or nearly normal knees. Therefore, it appears that the outcome is the same whether ACL-reconstruction is performed during the acute or chronic phase after injury.
2.5.2.2 Surgery

In active individuals, and recreational and professional athletes the consensus amongst surgeons is to reconstruct the ACL (Fu et al. 1999). The following graft materials are used during surgical reconstruction.

i Prosthetic (artificial) ligament replacement

Synthetic ligament replacements such as the Leeds-Keio (LK) polyester ligament were popular during the 1980s and early 1990s but the long-term outcomes have been shown to be poor, with a high incidence of osteoarthritis (Murray & Macnicol 2003; Fu et al. 1999).

ii Allograft

Using the biological soft tissue transplanted from a human donor has the advantages of avoiding donor site morbidity, decreasing surgery time and decreasing post-operative pain. However, the sterilisation process has been shown to decrease the tensile strength of the graft and there is an increased risk of inflammatory reaction. Therefore, these grafts may not be the best choice for athletic subjects (Fu et al. 1999).

iii Autografts

Using the biological tissue of the patient him/herself decreases the risk of disease transmission and has a low risk of reactive inflammation (Fu et al. 1999). One of the disadvantages of the autograft is that it causes weakening of structures from where it
was taken, i.e. donor site morbidity (Zarins & Adams 1988). The most popular autografts described in the literature are the bone-patellar tendon-bone (BPTB) graft and the two-strand or quadruple strand semitendinosis/gracilis (SG) graft. In recent years the hamstring graft has become more popular due to decreased reports of donor site morbidity (Fu et al. 1999) and less damage to the knee extensor apparatus (Beard et al. 2001).

A recent review of 9 randomised controlled trials compared ACL-reconstruction using either patellar tendon or hamstring tendon autografts compared objective outcomes, such as surgical technique, rehabilitation, instrumented laxity, isokinetic strength, and subjective outcomes – patellofemoral pain, return to pre-injury activity and Tegner, Lysholm, Cincinnati Knee Rating Scale and International Knee Documentation Committee-1991 scores (Spindler et al. 2004). The ACL-reconstructed group using hamstring graft in 3 of 7 studies showed a slight increase in ligament laxity on arthrometer testing while the ACL-reconstructed group using patellar tendon graft in 4 of 4 studies had greater pain with kneeling, even after a two-year follow-up period. One of 9 studies concluded that the ACL patellar tendon repair group had increased anterior knee pain. No significant differences were detected between the groups for other objective measurements such as range of motion, isokinetic strength or ligament laxity as measured by an arthrometer. Spindler et al (2004) concluded that the type of autograft did not appear to affect the outcome following ACL-reconstruction. This was confirmed by further studies which found no significant differences in functional scores, activity levels, and muscle strength between ACL-reconstruction operations using hamstring and patella tendon autografts (Beard et al. 2001; Feller & Webster 2003). However, Feller &
Webster (2003) reported increased pain on kneeling in the BPTB group and increased anterior laxity and tunnel widening in the hamstring tendon group, which is consistent with earlier studies.

2.5.2.3 Complications following surgery
Complications following ACL-reconstruction include graft failure, need for additional surgery, infection, deep vein thrombosis and nerve injury. A review of the literature comparing bone-patellar tendon-bone (BPTB) and hamstring (SG) tendon grafts suggested that graft failure was not significantly different between the two autograft groups, with a failure rate of 3.1% noted in the BPTB group compared to 4.1% in the SG group (Spindler et al. 2004). After ACL-reconstruction and accelerated rehabilitation, Shelbourne et al (1997) reported 2.6% of patients had a failure of their graft, at a mean of 2.5 years after surgery.

2.5.2.4 Rehabilitation following surgery
Risberg et al (2004) reviewed the effect of different rehabilitation protocols, such as supervised versus home-based rehabilitation programs, strength training, neuromuscular training and specific exercises used as part of rehabilitation following ACL-reconstruction. The review included randomised controlled trials (RCT) that evaluated active exercises or rehabilitation following ACL injury or reconstruction. Studies that looked at passive modalities were excluded. Studies were included based on strict methodological criteria: method of randomization, blinding, power analysis, compliance and loss at follow-up, clinical relevance of outcome measures, and adequate follow-up time. Thirty-three randomised controlled trials were included, of which 28 examined the
efficacy of rehabilitation or exercises following ACL reconstruction. From this review the following conclusions were made:

i. Rehabilitation protocols

There appears to be insufficient evidence in the literature that using an extended rehabilitation protocol of 8-months compared to a 6-month program following ACL reconstruction leads to improved outcome (Risberg et al. 2004).

ii. Supervised versus home-based rehabilitation programs

In the studies comparing supervised rehabilitation to minimal input/unsupervised programs, there is no evidence to suggest that all patients undergoing ACL reconstruction need regular and closely supervised rehabilitation. It seems that for a rehabilitation program to be effective, it needs to be monitored by a physiotherapist but not necessarily continuously (Beard & Dodd 1998; Risberg et al. 2004). This was confirmed by Feller et al (2004): the subjects in their study who chose to attend infrequently (mean of 1.9 visits) had satisfactory, if not better, outcomes at 12 months than subjects who attended physiotherapy regularly (mean of 26.5 visits). It may be that the subjects who chose to attend on a minimal basis were 'copers' before their surgery, or had inherent dynamic knee stabilising strategies. The study did not report pre-operative symptoms.

iii. Strength training

- Open kinetic chain (OKC) and closed kinetic chain (CKC) exercises.

There is little evidence to support the theory that OKC exercises increase the strain on the ACL, causing increased knee joint laxity or lead to anterior knee
pain. There is some evidence that carefully monitored OKC exercises using knee flexion angles greater than 40°, when started 6 weeks post-operatively, can significantly improve the quadriceps muscle strength without any injury to the graft. The literature also supports the use of CKC exercises in ranges of less than 60° as part of rehabilitation following ACL-reconstruction. A combined OKC and CKC exercise program resulted in a greater return to sport 6 months following ACL-reconstruction compared to an exercise program that consisted of CKC and functional exercises alone (Risberg et al. 2004).

• Neuromuscular Electrical stimulation (NMES)

There is evidence that using NMES in 65° of knee flexion as part of a normal rehabilitation program can improve isometric quadriceps strength without increasing the strain on the ACL (Risberg et al. 2004). NMES is reported to increase the Type II fibres in a muscle as opposed to Type I muscle fibres that are recruited in a voluntary muscle contraction.

iv. Neuromuscular training

Simply restoring the static restraints of the joint with ACL-reconstruction does not necessarily guarantee satisfactory outcome, since joint laxity has not been associated with functional outcome. Of the 3 randomised controlled trials that incorporated neuromuscular training as part of their rehabilitation, two investigated neuromuscular rehabilitation following ACL injury and one assessed neuromuscular training following ACL-reconstruction (Risberg et al. 2004). In the latter study the neuromuscular training group was found to have a larger percent increase in the isokinetic peak torques, although
both groups (the other group being a strength training program without neuromuscular training) showed improvement in the hamstring peak torque time. From this limited evidence, it appears that neuromuscular training can improve dynamic joint stability (Risberg et al. 2004). Further randomised controlled trials, with longer follow-up time are required, especially following ACL-reconstruction surgery.

v. Specific exercises

Risberg at al (2004) concluded that all the studies examining specific exercises as part of a rehabilitation program, such as isokinetic strength and stair climbing versus ergonomic cycling had significant flaws (for example the studies made no mention of methods of randomisation, compliance with exercise programs or loss of follow-up was not reported) and therefore their results should be interpreted with caution. They suggested that future randomised controlled trials need to be better planned, stating power calculations, with randomised groups and controlling for bias. Sufficient follow-up data should also be obtained. From this systematic review of the literature, there appears to be no single treatment that is more effective (Risberg et al. 2004). Future well-executed research is needed in this field, especially in neuromuscular training.

vi. Conservative versus accelerated rehabilitation

The role of conservative versus accelerated rehabilitation following ACL-reconstruction is controversial. Shelbourne et al (1997) found that patients who followed an accelerated rehabilitation program (where subjects returned to sport-specific activities at a mean of 6.2 weeks post-operatively) following PT autograft demonstrated full ROM, good stability, strength and return to full function at long-term follow-up (mean of 4.0 years
post-operatively). The patients were allowed to return to sport-specific activities after greater than 65% of quadriceps strength had been attained relative to the other leg. However, in a prospective comparative study Majima et al (2002) reported that nine months after ACL-reconstruction using SG autograft, there was no significant difference in anterior laxity or muscle torque between a group that followed an accelerated rehabilitation program and a group that followed a conservative program. The accelerated rehabilitation group did have a significantly increased incidence of joint effusion during their rehabilitation, which may have negative effects on the joint cartilage or the graft. No long-term results are available to assess whether accelerated rehabilitation could lead to early joint degeneration.

2.5.2.5 Outcome and prognosis following ACL-reconstruction

i. Strength

In the past great emphasis was placed on muscle strength as a predictive outcome measure after ACL-reconstruction. Residual quadriceps weakness is a common finding following ACL-reconstruction (McHugh et al. 2002; Novak et al. 1996; Keays et al. 2001; Natri et al. 1996) (Table 2.2). Arvidsson et al (1981) found that extensor muscle torque remained less in the involved limb of ACL-reconstructed individuals as many as 5 to 10 years after the surgery, although the lean thigh volume was not measured in the study. The finding of reduced extensor muscle torque lead Arvidsson et al (1981) to recommend that “continued training of muscle strength and endurance will probably be necessary indefinitely for the majority of these individuals”. Despite this comment a number of their subjects were able to either participate in their normal sports (25.3%) or only make slight modifications to their level of sport activity (43.7%). There is evidence
that the decreased muscle strength following ACL-injury, and subsequent ACL-
reconstruction, could be due to mechanisms other than lack of training or disuse of the
injured limb due to pain or instability. Cooper et al (1996) hypothesised that residual
quadriiceps weakness is centrally mediated, and that this may play an important protective
role in preventing excessive anterior tibial translation by unopposed quadriiceps activity.
The authors conclude that rehabilitation may be more successful if exercises focus on
restoring normal activation of muscles rather than on high intensity strengthening

The recovery of peak flexion torque appears to be greater than 90% after ACL-
reconstruction (Table 2.3). One study demonstrated that peak knee flexion torque was
reduced at angles of 90° or greater following ACL-reconstruction using a
semitendinosus/gracilis autograft (Nakamura et al. 2002). This was confirmed in a study
by Tashiro et al (2003) who found that isometric and isokinetic peak hamstring force was
decreased at flexion angles of greater than 70° following ACL-reconstruction using either
semitendinosus or SG autograft, even 18 months following surgery. The clinical
importance of this finding may be of little consequence since not many sporting activities
involve deep knee-flexed positions.
Table 2.2. Quadriceps strength deficits (involved/uninvolved limb) following ACL-reconstruction

<table>
<thead>
<tr>
<th>Study</th>
<th>Mean quadriceps strength deficit @ 60°/s</th>
<th>Mean quadriceps strength deficit @ 180°/s</th>
<th>Mean quadriceps strength deficit @ 240°/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Novak et al (1996) (min 2 years f/up) (PT)</td>
<td>11%</td>
<td>7%</td>
<td>4%</td>
</tr>
<tr>
<td>Jarvela et al (2002) (7 years f/up) (PBTB)</td>
<td>10.3%</td>
<td>4.5%</td>
<td>5.2%</td>
</tr>
<tr>
<td>Keays et al (2001) (at 6 months f/up) (SG)</td>
<td>12%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Keays et al (2003) (at 6 months f/up) (SG)</td>
<td>12%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wojtys &amp; Huston (2000) (at 18 months f/up) (PT)</td>
<td>10%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2.3. Hamstring strength deficits (involved/uninvolved limb) following ACL-reconstruction

<table>
<thead>
<tr>
<th>Study</th>
<th>Mean hamstring strength deficit @ 60°/s</th>
<th>Mean hamstring strength deficit @ 180°/s</th>
<th>Mean hamstring strength deficit @ 240°/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jarvela et al (2002) (7 years f/up) (PBTB)</td>
<td>0%</td>
<td>0%</td>
<td>2.9%</td>
</tr>
<tr>
<td>Keays et al (2001) (at 6 months f/up) (SG)</td>
<td>10%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Keays et al (2003) (at 6 months f/up) (SG)</td>
<td>10%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

It is important to note that Wojtys et al (2000) found no improvement in quadriceps peak torque at 6-month follow-up (66% pre-operative versus 64% at 6-months follow-up), even though subjective and functional rating had improved significantly by this time. The study found a significant increase in quadriceps strength only at one year following surgery (81%). This indicates that a mismatch occurs between functional and muscle strength changes, and therefore that strength alone does not improve outcome. Other factors, such as neuromuscular control, biomechanical or psychological factors, may therefore play a role in subjective rating of functional improvement.

ii. Functional outcome

Following ACL-reconstruction using semitendinosus/gracilis autograft, a study found a significant correlation between quadriceps strength indices and functional tests (as
measured by five functional stability tests) but no correlation was found between hamstring strength and functional stability (Keays et al. 2003). The authors concluded that the correlation between quadriceps strength and function suggested that a re-enforcement of quadriceps strengthening in the rehabilitation program following ACL-reconstruction was necessary. However, in another study no correlation was found between strength deficits and functional outcome (Keays et al. 2001). Wojtys and Huston (2000) examined neuromuscular performance following ACL-reconstruction using a patellar tendon autograft. Although 80% of the subjects reported that they returned to their pre-operative levels of function 18 months following surgery, objectively most subjects' muscle function had not returned to normal, which indicates that there may be no direct link between perceived function and objective outcome measures following ACL-reconstruction.

iii. Ligament stability
In the past ligament stability has often been used to assess the satisfactory outcome of surgery. But several recent studies showed no evidence that there is a relationship between ligament stability or lack thereof (i.e. laxity) and functional outcome following ACL reconstruction (Seto et al. 1988; Kocher et al. 2004; Kocher et al. 2004).

iv. Movement patterns
Gait adaptations in ACLD patients before and at intervals after ACL-reconstruction have been investigated (Knoll et al. 2004). In the acute ACL-deficient group a ‘quadriceps avoidance’ gait pattern was observed, while no significant differences were found between the chronic ACL-deficient group and a control group, indicating some degree of
adaptation to the loss of the normal restraints and input from the ACL. Following ACL-reconstruction, gait patterns and EMG activity return to normal values after 8 months (Knoll et al. 2004). Conversely, Devita et al (1997) demonstrated that the initial response following ACL-injury appears to be an increase in knee extensor torque throughout the stance phase of gait. This pattern persisted 5 weeks after ACL-reconstruction. Future studies should include a longer follow-up period to determine when this gait adaptation changes. In a study analysing the EMG patterns around the knee during functional activities, Ciccotti et al (1994) found that following ACL-injury, rehabilitation does not restore normal EMG patterns during functional tasks such as walking, stair climbing and running, as subjects still required increased muscle activity to perform these activities. After ACL-reconstruction, using BPTB autograft, subjects’ EMG patterns returned to those observed in normal subjects at a mean of 28 months (18-36 months) after the time of surgery.

v. Neuromuscular control

Although there is evidence that the graft is repopulated and re-inforced by collagen from fibroblasts, as well as undergoing a process of revascularisation (Fu et al. 1999), there is no evidence that the graft regains sensory receptors that restores afferent input between the ACL and the central nervous system. This may also have implications for other functions of the nervous system such as proprioception.

vi. Proprioception

There appears to be contradictory evidence in the literature about whether proprioception improves after ACL-reconstruction. In a study on proprioception following ACL-
reconstruction, Bonfim et al (2003) found that patients still had decreased sensory and motor performance up to 18 months after ACL-reconstruction. They concluded that reconstructing the ACL did not improve proprioception, due to the loss of afferent input from mechanoreceptors in the damaged ACL. This was confirmed by Ageberg (2002) who reported, in a review of the literature on the effect of a ligament injury on the neuromuscular function of a joint, that proprioception of the knee joint remained decreased after an ACL injury or reconstruction, despite rehabilitation. In this review proprioception was measured by the threshold for detecting passive motion.

However, in contrast, Hopper et al (2003) found no difference in the joint position sense between the injured and uninjured limbs of subjects who underwent ACL-reconstruction between 12 and 16 months previously. This study measured joint position sense in a weight-bearing position, as opposed to the non-weight-bearing method used in the study by Bonfim et al (2003), which attempted to isolate the proprioceptive input to the ACL alone. The authors described their methods as more clinically relevant and an approach which 'endeavoured to describe the status of the knee as a function of the myriad of structures responsible for knee joint proprioception'. The study did not compare the subjects with controls. Bilateral proprioception deficits have been described in individuals with a unilateral ACL injury (Ageberg 2002) and this may have affected the results from this study. Further research is therefore required to assess whether proprioception is restored following ACL-reconstruction.
vii. Osteoarthritis

Daniel et al (1994) found a higher rate of joint abnormalities, as measured by radiograph and bone scan evaluation, in patients who had ACL-reconstruction, compared to those who did not have ligament surgery. This could be explained by the fact that these individuals did have a higher incidence of meniscal repair at the time of reconstruction. However, even those individuals who did not need meniscal repair at the time of the ACL-repair demonstrated higher incidence of degenerative joint disease. Another study (von Porat et al. 2004) found a high prevalence of osteoarthritis 14 years after an ACL tear in male soccer players. More advanced radiographic changes (grade 2 or higher) were seen in 41% of the injured knees compared to only 4% of the uninjured knees. There was no difference between the players who were treated conservatively or surgically. These findings imply that ACL reconstruction does not necessarily prevent the development of osteoarthritis in the knees of active individuals.

2.5.2.6 Psychological response following ACL-reconstruction

Kvist et al (2005) investigated psychological hindrances that may influence an athlete's return to sport following anterior cruciate ligament reconstruction. They found that only fifty-three percent of the patients in the study (n = 62) returned to their pre-injury sport activity levels 3-4 years after ACL reconstruction. Twenty-four percent of the subjects who did not return to their previous level of activity (7/29) displayed a greater fear of re-injury due to movement, as measured by the Tampa Scale of Kinesiophobia. This study suggests that psychological factors, such as the fear that movement could cause re-injury, could decrease the ability of rehabilitation and influence return to pre-injury levels of activity following ACL-reconstruction. Kvist et al (2005) did not investigate any factors
that may have caused this fear of movement e.g. decreased proprioception or impaired neuromuscular function.

2.6 Conclusion

From the literature it is evident that the ACL plays an important role in the static and dynamic stability of the knee joint and injury of this ligament can lead to a cascade of symptoms including instability, pain and swelling. The ACL has an important role as a sensory organ in joint proprioception. Injury to the ligament leads to decreased proprioception and may cause functional instability of the knee.

The two most commonly used grafts in ACL-reconstruction are the bone-patellar-tendon-bone (BPTB) graft and semitendinosus/gracilis (SG) autograft. Both these techniques have been extensively investigated, comparing (i) the long-term outcome of each graft with outcomes such as isokinetic strength, range of motion (ROM), laxity and instability, or (ii) the outcomes of the two kinds of graft relative to each other. However, during studies following ACL-reconstruction, subjects were all grouped together, or groups were created based on the type of graft the patient had, to investigate strength, stability or functional outcome rather than grouping them according to their functional ability.

Individual variability following ACL injury has been shown to occur and at least two distinct groups with different outcomes can be identified. Individuals who are able to return to a high level of function (Level I sports, at least weekly) after their injury without episodes of giving way or instability can be classified as ‘copers’. On the other hand ‘non-copers’ are unable to return to their pre-injury level of sport participation or activity
due to repeated episodes of giving way (Eastlack et al. 1999). Failure to recognise the differences between copers and non-copers, and how they respond following injury, could account for the inconsistencies found in the literature where most studies tended to group all subjects with ACL injury together. Fitzgerald et al (2000) developed a screening examination to identify copers. However, there have been no studies to investigate whether copers and non-copers can also be identified following ACL-reconstruction and no screening examination has been developed to distinguish between these potential groups.

These individual differences in dynamic knee stabilising strategies may also affect a subject's outcome following ACL-reconstruction. In one study which attempted to identify factors that may predict residual quadriceps weakness following ACL-reconstruction, the authors found that pre-operative EMG deficit of the quadriceps muscle was the best predictors of functional performance (hop test) at 6 months follow-up (McHugh et al. 2002). This may indicate that a neuromuscular deficit pre-operatively could result in reduced or poorer functional outcome following reconstruction, and create a non-coper.

Objective measures of ligament stability or muscle strength following ACL-reconstruction does not correlate well with functional outcome (Kocher et al. 2004; Seto et al. 1988). What then does determine satisfactory outcome following ACL-reconstruction? This is an important question to help focus future research on how to go about improving the functional outcome following expensive ACL-reconstruction and
time-consuming rehabilitation, and ultimately ensure the speedy, successful return of athletes to their previous level of function.

This study therefore aimed to (i) compare ACL-reconstructed individuals to a normal, healthy control group to assess whether there are any differences in self-reported function, muscle strength and functional outcome measures between the groups, and (ii) separate individuals who had undergone ACL reconstruction into specific ‘coper’ or ‘non-coper’ groups according to self-reported function, and to then correlate these identified groups with the outcomes measures to assess whether there are any significant differences between the identified groups.
Chapter 3

Neuromuscular control and physical performance following anterior cruciate ligament reconstruction using a semitendinosus/gracilis double-strand graft: are there different levels of coping?
Introduction

As described in the literature review, different levels of functional ability have been identified following ACL-injury (Snyder-Mackler et al. 1997; Eastlack et al. 1999). Researchers have proposed that two distinct types of responders can be identified. Individuals who were able to return to a relatively high level of function after their injury without episodes of giving way or instability of the knee joint were classified as ‘copers’. On the other hand ‘non-copers’ were unable to return to their pre-injury level of sport participation or activity due to repeated episodes of giving way of their knee joint after ACL injury. Failure to recognise the differences between copers and non-copers, and how they respond following injury, could account for the inconsistencies in outcome measures described in the literature, where most studies tended to group all subjects with ACL injury together when studying different outcome measures.

Several studies have investigated differences between copers and non-copers: knee joint laxity (Snyder-Mackler et al. 1997; Eastlack et al. 1999), walking patterns (Rudolph et al. 1998; Alkjaer et al. 2003) and rehabilitation (Fitzgerald et al. 2000). To our knowledge, no study has investigated whether these differences in an individual’s ability to dynamically stabilise their knee following injury may also affect a subject’s outcome following ACL-reconstruction.

The objectives of this study were to (i) compare ACL-reconstructed individuals to a normal, healthy control group to assess whether there are any differences in self-reported function, muscle strength or functional outcome measures, and (ii) separate individuals who had undergone ACL reconstruction into specific ‘coper’ or ‘non-coper’ groups
according to self-reported function, and to then correlate these identified groups with the outcomes measures to assess whether there are any significant differences between the identified groups.

3.1 Methodology

3.1.1 Experimental design

A cross-sectional descriptive study design was used.

3.1.2 Recruitment procedure

The study was approved by the Research Ethics Committee of the University of Cape Town (Appendix 1). A list of potential subjects was compiled from the medical notes of all the ACL-reconstruction operations performed by the orthopaedic consultant, Dr. Willem van der Merwe, between March 1999 and May 2003. A total of 107 potential subjects were identified. These potential subjects were contacted via telephone to enquire whether they would be willing to participate in the study (Appendix 2: Telephone Recruitment Form).

From the list of 107 potential subjects, 66 were unobtainable because their contact telephone number were incorrect; they had moved house and did not leave a forwarding address or contact number; or the contact telephone number was no longer in use. Nine people declined to partake in the study due to time restrictions. Four people were excluded because of graft failure or further surgery to their affected knee joint. One candidate was excluded due to multiple injuries and ongoing mobility problems following a motor vehicle accident sustained after his ACL-reconstruction surgery.
Twenty-seven potential subjects indicated that they would be willing to participate in the study. Six of these potential subjects never returned phone calls to schedule an appointment. Four other subjects cancelled or failed to attend their appointments. A total of seventeen subjects were therefore included in the study.

An orthopaedic consultant, Dr. Willem van der Merwe, performed all the ACL-reconstructions. Although the evidence from the literature suggests no difference in the long-term functional outcome between PTBT and SG graft, it was decided to limit the study to one type of graft (SG double-stranded graft) to make the population more homogeneous.

The subjects were included if

(i) they had an ACL reconstruction at least two years ago and not more than five years ago;
(ii) the subject's contralateral knee joint was normal and had no other musculo-skeletal injuries that could prevent them from taking part in their normal sporting activities;
(iii) they had no other medical problems which prevented exercise and
(iv) at the time of the testing all subjects had a full knee range of motion, no pain or joint effusion and were able to tolerate hopping on the reconstructed limb.
Subjects who had failure of the graft or a revision of their graft were excluded from the study. Any other internal injuries sustained at the time of the original injury and/or corrected during surgery were documented.

3.1.3 Consent
Before testing commenced all subjects were required to familiarise themselves with the subject information sheet (Appendix 3) and informed consent was obtained from each subject (Appendix 4). All subjects were required to complete a medical questionnaire to exclude any serious medical conditions that could be a contra-indication to physical exercise (according to the American College of Sports Medicine guidelines, 2000) (Appendix 5).

3.1.4 Surgical procedure
All subjects had undergone an arthroscopic double-stranded semitendinosus/gracilis autograft using the tendon from the ipsilateral limb. The graft was then placed through bone tunnels in the femur and tibia. Distally, the graft was secured using a dissolvable screw fixation on the tibial tunnel. Arthroscopic partial meniscectomy was performed on eight of the 17 subjects. Post-operatively, the subjects did not wear a brace and full immediate weight-bearing was encouraged.

3.1.5 Physiotherapy and leg dominance
Any physiotherapy treatment undertaken by the subject after surgery was documented (Appendix 6 – Personal Demographics and Treatment). This included information about
how many sessions they attended, the duration of treatment and what the treatment involved.

Leg dominance was not tested physically. Each subject was required to fill in a questionnaire on personal demographics (Appendix 6), which included a question about leg dominance. The researcher was available to explain what was meant by leg dominance. No subjects had any queries about the definition of leg dominance, and all subjects answered the question.

3.1.6 Anthropometric data

The following anthropometric data were collected from each subject (Appendix 7: Anthropometric data sheet):

- Weight (kg): the subject was weighed on a standard scale.

- Height (cm): the height of the subject (without shoes) was measured with a standard height measure.

- Lean thigh volume (cm³): the anterior mid-thigh skinfold measurement, the sub-gluteal, mid-thigh and above-knee circumferences were recorded for both limbs and used to calculate the lean thigh volume. This technique assumes that the thigh has the shape of a truncated cone and the measurements were substituted into the following equation:

First the volumes of the 2 cones were calculated:

Cone 1:

\[ a_1 = \pi \left[ \frac{(\text{subglut girth measurement cm/2}\pi)}{2} - (\text{thigh skinfold thickness cm/2}) \right]^2 \]

\[ a_2 = \pi\left[ \frac{(\text{midthigh girth measurement cm/2}\pi)}{2} - (\text{thigh skinfold thickness cm/2}) \right]^2 \]
Volume of cone 1 = \( \frac{1}{3} \times h \times (a_1 + a_2 + \sqrt{a_1 a_2}) \)

Cone 2:

\[
a_2 = \pi \left[ \left( \frac{\text{mid-thigh girth measurement cm}}{2\pi} \right) - \left( \frac{\text{thigh skinfold thickness cm}}{2} \right) \right]^2
\]

\[
a_3 = \left[ \left( \frac{\text{above-knee girth measurement cm}}{2\pi} \right) - \left( \frac{\text{thigh skinfold thickness cm}}{2} \right) \right]^2
\]

Volume of cone 2 = \( \frac{1}{3} \times h \times (a_2 + a_3 + \sqrt{a_2 a_3}) \)

Lean thigh volume (cm³) = volume of cone 1 + volume of cone 2

This technique was adapted from Katch and Katch (1974), and has been validated against lean thigh volume assessed by MRI (Knapik et al. 1996).

3.1.7 MRI

Each subject underwent an MRI scan (Esaote Biomedica Artoscan, Genoa, Italy) of the ACL reconstructed knee, as part of the study, to verify the integrity of the graft and exclude damage to any other internal structures.

MRI data was also collected with the intention of assessing the position of the graft. It is possible to determine a three-dimensional image of the position of the graft compared to the 'ideal' or anatomical position. This data can then be used to assess whether the position of the graft correlates to self-reported function (KOS-ADLS and CKRS-SAS), quadriceps and hamstring muscle strength (concentric and eccentric testing) or functional outcome measures (hop tests). The results of the MRI scan data will not be discussed in this thesis, and will be reported on at a later date.
3.1.8 Measurement of knee laxity

The laxity of the graft in the involved limb of the ACL-reconstructed group, or the ACL-ligament in the control group was measured at maximum manual testing using a KT-1000 arthrometer (MedMetric, San Diego, CA) and compared to the uninvolved or non-dominant limb. The KT-1000 arthrometer was designed to measure mechanical stability of the knee joint. The outcome measure was anterior tibial translation in millimetres.

3.1.9 Self-reported measures of knee function

Each subject in the study was required to complete three subjective measures of knee function. The self-reported measures of knee function used in this study were (i) the Activities of Daily Living Scale portion of the Knee Outcome Survey (KOS-ADLS), (ii) the Cincinnati Knee Rating System (CKRS) - Sports Activity Scale (CSAS) and (iii) the global rating of knee function scale (GRS).

Each subject was asked to complete the KOS-ADLS, which is a subjective measure of the functional limitations a patient with knee pathology perceives they commonly experience (Appendix 8) (Irrgang et al. 1998). The KOS-ADLS is a questionnaire based on the individual’s perception of their functional status. The questions evaluate the severity of symptoms experienced by patients during their activities of daily living, and their ability to perform various activities. Each subject’s score is expressed as a percentage, which is determined by dividing the subject’s score by the total possible score (80) and then multiplying by 100. A maximum score of 100% correlates to no symptoms and no difficulty during activities of daily living.
The subjects also completed a questionnaire on sport participation, the CSAS (Appendix 9) (Noyes F.R. et al. 1984; Noyes et al. 1989; Barber-Westin & Noyes 1999), which contributed towards the functional score of their knee. The CSAS was designed to assess (i) the type of sporting activity and the forces involved during the sport (e.g. jumping, hard twisting and pivoting) and (ii) the frequency of sport participation (i.e. times per week) (Barber-Westin & Noyes 1999; Phillips et al. 2000). The CSAS was found to have adequate reliability (intraclass correlation coefficients > 0.70) and good content and construct validity when used in studies of patients after ACL-reconstruction (Barber-Westin et al. 1999).

Each subject completed a global rating of their present knee function from 0-100%, where 100% corresponded with their pre-injury levels (Appendix 10). All the subjects in the control group also completed the self-reported measures of knee function.

3.1.10 Episodes of giving way

Each subject was asked to state how many episodes of giving way they have experienced since their ACL-reconstruction. The number of episodes of giving way was recorded as part of the subjective outcome measures of the ACL-reconstructed knee.

3.1.11 Four specific hop tests

The hop tests used in this study was described by Noyes et al (1991) as ‘performance-based measures of knee function’. Each subject was required to perform four specific hop tests (Appendix 11: Hop tests data sheet) (Noyes et al. 1991; Lewek et al. 2003):
• **a cross-over hop for distance:** the subject started at a specific marker with their hands behind the back. The subject was instructed to hop forward across a 15.2cm (6 inch) wide tape for three consecutive hops on the same leg, maintaining their position and regaining their balance after every hop before commencing the next one (Figure 3.1). The distance covered was measured in centimetres.

Figure 3.1 Schematic representation of the cross-over hop (Noyes et al. 1991)

![Cross-over Hop Diagram](image)

• **straight triple hop for distance:** the subject started at a specific marker with their hands behind the back. The subject was instructed to jump forward for three consecutive hops on the same leg, maintaining their position and regaining their balance after every hop before commencing the next one. The distance covered was measured in centimetres.

• **single hop for distance:** the subject started at a specific marker with their hands behind the back. The subject was instructed to jump forward as far as possible to land on the same leg and to hold that position until they regained their stability. The distance jumped was measured and recorded in centimetres.

• **timed 6-meter hop test:** the subject started at a specific marker. A distance of six metres was measured and marked with a line on the floor. The subject was instructed to jump on the same leg and cover the distance as quickly as possible keeping their
hands behind the back. The time that it took to complete the six-meter distance was taken using a stopwatch and recorded in seconds.

By keeping their hands behind their backs, the subject's trunk is angled forward in relation to the centre of gravity and causes an increase in eccentric knee flexion control during the hop, thus placing greater demand on the quadriceps. This controlled posture also reduced the use of momentum generated by the trunk and arms, which could act as confounding variable (Keays et al. 2003).

Each subject performed the hop tests in a standardised way: the subject performed each hop test on the uninvolved side first, followed by the involved limb. The choice of which limb performed each test first was therefore not randomised for the ACL-reconstructed individuals, in order to familiarise each subject with the test, and decrease the likelihood of injury to the graft. For the control group the limb to be measured first was randomised. For each hop test the subject performed two practice trials first, and then repeated three trials for each limb. The average of the three trials was used. The same examiner performed all tests.

For the single, cross-over and triple hops, the average score of the involved limb was calculated. This was then divided by the average score for the uninvolved limb and multiplied by a 100 to calculate the limb symmetry index. For the timed hop the limb symmetry index was calculated by dividing the average score of the uninvolved side by the average score of the involved side and multiplied by 100 (Noyes et al. 1991). EMG signals from the vastus lateralis (VL), vastus medialis (VM), semitendinosus (ST), and
biceps femoris (BF) muscles were collected during all the hop tests using the protocol described below (see 3.1.14).

3.1.12 Step up/down test

Each subject was instructed on how to perform a functional step up/step down test. The subject stood in front of a 30 cm high wooden step. The same wooden step was used for all the trials. He/she was instructed to step up and then step down forward off the step, leading with the same leg during both the step up and down phase. The uninvolved leg was used first and then the involved leg for the ACL-reconstructed individuals, while for the control group the leading limb was randomised. The subject familiarised themselves with the step activity before beginning the trial by performing two practice trials.

Once the subject was familiarised with the protocol, he/she was instructed to stand motionless in front of the step, while keeping his/her hands behind their back. On instruction from the researcher the subject started the step up test for a count of 3 seconds, stopping for 3 seconds at the top of the step to regain their stability and then commenced the step down test for a count of 3 seconds. Each test concluded when the supporting leg had reached the floor again, and the subject was stationary. Each subject performed three trials for each limb.

The activation of EMG activity in the VMO and VL muscles was recorded during the step up/down test using the protocol described below. The relative time of onset of muscle activity in these muscles were determined using visual assessment. Visual
determination of EMG onset has been proven to be highly repeatable between days when compared to a range of computer-based techniques (Hodges & Bui 1996).

The time of onset of the muscle activity of the VMO relative to VL EMG activity was calculated by subtracting VMO EMG onset from VL [VMO - VL] (Cowan et al. 2000).

3.1.13 Assessment of isokinetic strength

Quadriceps and hamstring muscle strength was determined using a Biodex isokinetic dynamometer (Biodex Medical Systems, Shirley, New York). Subjects all followed the same standardized procedure for the application of equipment, familiarization and data collection.

Subjects were seated in the chair of the dynamometer and the anatomical axis of the knee was aligned with the axis of the dynamometer. The distal aspect of the arm of the dynamometer was placed 4 cm proximal to the medial malleolus. The dynamometer seat back was placed at 100°. The ankle was fastened to the dynamometer arm, and the chest, thigh and waist was fastened to the dynamometer seat with stabilisation straps to minimize extraneous movements.

Verbal encouragement was given in a consistent manner. The same examiner performed all the tests. The quadriceps and hamstring muscle strength tests were performed for both limbs of all the subjects and controls. For all the testing, the uninvolved leg was tested first followed by the involved leg for the ACL-reconstructed individuals, to minimize the risk of injury. In the control group the limb that was to be tested first was randomized.
Isometric testing: Subjects performed isometric testing to measure maximum isometric voluntary contraction (MVIC) at 60° of knee flexion, first for the quadriceps muscle and then for the hamstring muscle. Subjects were asked to perform three sub-maximal contractions for five seconds each (two at 50% and one at 75%) before the test started, as part of the warm-up. The subject then performed three maximum contractions of five seconds each, with a one-minute rest between each contraction. Verbal instructions were to push as hard as they were able to. The mean value of the three contractions was used as raw data.

Isokinetic testing: Each subject was tested for concentric quadriceps and hamstring strength at 60°/s and 180°/s. Each subject performed five sub-maximal contractions to familiarize him/herself with the technique. Peak torque (Nm) was determined at the speeds of 60 and 180°/s. Five test efforts were performed for flexion and extension at 60°/s and ten repetitions at 180°/s with a two-minute rest between bouts (Natri et al. 1996). Subjects were encouraged verbally to push as hard and as fast as they were able to. The mean value for both speeds was used as raw data.

Reactive/eccentric testing: Each subject then performed an eccentric test for quadriceps and hamstrings muscles at 60°/s. The test was carefully explained and demonstrated to each subject, simulating dynamometer movements. Subjects then performed three warm-up trials, and the force was adjusted if the subject could not perform a smooth movement through the range of motion available. Subjects performed five maximum contractions.
during testing. Verbal instructions were to resist the dynamometer movement as hard as they were able to. The mean value of the five contractions was used as raw data.

One of the ACL-reconstructed subjects was unable to perform the eccentric muscle testing despite careful instructions due to cognitive impairment reasons. The statistical analysis was adjusted to reflect this smaller sample size ($n = 16$) for the eccentric strength data. EMG data was collected simultaneously during the isokinetic testing for the VL, VM, ST and BF muscles.

3.1.14 Electromyographic evaluation

The muscle function of the muscles around the knee was recorded using electromyography (EMG). To measure EMG activity, EMG surface electrodes (Blue Sensor, Medicotest A/S, ølstykke, Denmark) were placed over the following muscles: vastus medialis (VM), vastus lateralis (VL), semitendinosus (ST) and biceps femoris (BF). Prior to attaching the surface electrodes the skin was carefully prepared: the hair was shaven off, the outer layer of the epidermal skin cells was abraded and the remaining oil and dirt removed using an alcohol wipe. This enhances the electrode adherence and conduction of the EMG signal.

Surface electrodes were positioned following a standardised protocol described in the literature (Delagi et al. 1994; Rainoldi et al. 2004):

- The electrode to measure VM activity was placed on the main belly of the muscle approximately 8 cm proximal to the superior border of the patella, in a line directly connecting the middle of the superior border of the patella with the
anterior superior iliac spine (ASIS), and 5 cm medial to this line in a perpendicular direction.

- The electrode to measure VL activity was placed 3 cm anterior to the midpoint of the line connecting the lateral femoral epicondyle with the greater trochanter of the femur.
- The electrode to measure ST activity was positioned midway on the line that connects the medial epicondyle of the femur with the ischial tuberosity.
- The electrode to measure BF activity was placed midway on the line that connects the fibula head with the ischial tuberosity.

Surface electrodes were placed 2 cm apart on the muscle belly of each muscle described, parallel to the underlying muscle fibres. Electrode position was secured using Elastoplast – Rigid Strapping plaster (Beiersdorf, Germany), and held in position with Elastoplast – Fabric Roll plaster (Beiersdorf, Germany).

The electrodes were linked to an amplifier box, which transmits a signal telemetrically to a computer with Myoresearcher Software (Noraxon USA Inc. Scottsdale, Arizona). All EMG data was sampled at 2000Hz and filtered using a 50Hz (RJ-50) filter to reduce interference from electrical sources. The raw data was then filtered with a 15 – 500 Hz bandpass filter to remove movement artefact, while smoothing of the data was done using the RMS (root mean square) (50ms window) method.

The normalisation of the EMG data was performed by expressing each subject’s data as a percentage of the EMG data from the MVC during isometric testing. By normalising
EMG data, rather than using raw EMG data, muscle activity from different subjects can be compared to each other without the confounding effects that can derive from large intersubject variability, such as electrode placement variation or subcutaneous body fat distribution.

3.1.15 Classification of ACL-reconstructed individuals as copers or non-copers

The second part of the study attempted to separate individuals who had undergone ACL reconstruction into specific 'coper' or 'non-coper' groups according to their reported episodes of giving way, hop test, self-report of function and global rating of function score.

In their study Lewek et al (2003) classified copers as individuals who scored:

(i) timed hop test ≥ 80% compared to the uninjured limb;
(ii) KOS-ADLS ≥ 80%;
(iii) Global rating ≥ 60% compared to their pre-injury levels; and
(iv) Not more than one episode of giving way

For the purpose of the present study this classification has been modified due to the higher scores achieved by the subjects following ACL-reconstruction in the self-reported functional outcome measures than in the study by Lewek et al (2003) on ACL-deficient subjects.

For the purpose of this study the following classification criteria were used:
Group 1: will be termed ‘copers’ for the purpose of this study. Copers were classified as individuals who scored:

(i) Global rating ≥ 90%
(ii) Timed hop test ≥ 90%
(iii) KOS-ADLS ≥ 90%
(iv) No episodes of giving way

Group 2: will be termed ‘non-copers’ for the purpose of this study. ‘Non-copers’ will be classified as individuals who scored:

(i) Global rating < 90%
(ii) Timed hop test < 90%
(iii) KOS-ADLS < 90%
(iv) One or more episodes of giving way

After these groups were identified their various neuromuscular outcomes were compared to assess whether there were any significant differences in neuromuscular function between the identified groups.

3.1.16 Statistical Analysis
The recorded data was transferred to a spreadsheet and analysed using Statistica 7.0 (Version 7, StatSoft, Inc). All data was expressed as the difference between the ACL-reconstructed and uninjured limbs in the ACL-reconstructed group, and the dominant and non-dominant limbs in the control group. The data between the ACL-reconstructed and
control groups were compared using an unpaired t-test, independent, by groups. The level of significance was set at $p < 0.05$.

In the second part of the study all data was expressed as the difference between the ACL-reconstructed and uninjured limbs in the coper and non-coper groups. The data between the coper and non-coper groups were compared using independent t-tests, and the level of significance was set at $p < 0.05$.

### 3.2 Results

#### 3.2.1 The ACL reconstructed individuals versus control group

3.2.1.1 Subject characteristics

Of the 107 potential subjects, 27 (25%) were accessible, and agreed to participate in the study. Six of these subjects never returned phone calls to schedule an appointment, while four subjects cancelled or failed to attend their appointments. None of the subjects who were tested were excluded based on the exclusion criteria.

Therefore, seventeen subjects (9 men and 8 women) (16% of potential subjects) aged between 20 and 47 years (mean = 29.9 years; SD = 9.5) were recruited from a cohort of patients who underwent unilateral two-stranded semitendinosis/gracilis ACL reconstruction between 1999 and 2003. In 8 subjects the right leg was the involved limb and in 9 cases the left leg was the injured limb. In four cases the subject had additional procedures performed at the time of the ACL-reconstruction: three had meniscal repairs and one subject had a lateral collateral repair. The mean time since surgery was 34.6
months (range: 24 – 49 months). All the subjects had full range of motion and no effusion at the time of testing.

A healthy, uninjured control group (4 men and 6 women) of 10 age- and sport-participation level-matched subjects (mean = 30 years; SD = 7.3) were recruited to measure normal data and to control for any bilateral adaptations that may occur at cortical level following ACL-injury or reconstruction (Ageberg 2002). The right leg was the skill dominant leg in eight of the control group while the left leg was the dominant leg in two controls. On KT-1000 testing, all the subjects who had undergone ACL-reconstruction, as well as the subjects in the control group, had less than 3mm difference in anterior displacement between limbs during maximal manual testing at both 45 and 90° knee flexion.

There was no significant difference between the limbs of the ACL-reconstruction (ACLR) and control groups when measured for age, body mass, height (Table 3.1) and differences in lean thigh volume between limbs (LTV) (Figure 3.2).

<table>
<thead>
<tr>
<th>Group</th>
<th>n</th>
<th>Age (years)</th>
<th>Body mass (kg)</th>
<th>Body height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>SD</td>
<td>Average</td>
</tr>
<tr>
<td>ACLR</td>
<td>17</td>
<td>29.9</td>
<td>9.5</td>
<td>74.3</td>
</tr>
<tr>
<td>Controls</td>
<td>10</td>
<td>30.0</td>
<td>7.3</td>
<td>70.4</td>
</tr>
</tbody>
</table>

|         |    | Average    | SD             | Average          | SD               |
|---------|----|-------------|----------------|------------------|
|         |    | 169.1       | 6.7            | 172.9            | 10.5             |
3.2.1.2 Rehabilitation

Following the ACL-reconstruction all but one of the subjects underwent physiotherapy treatment to help reduce swelling, regaining full ROM and restoring function. None of the subjects has received physiotherapy in the past six months on the involved limb.

3.2.1.3 Self-reported measures of knee function

The controls scored significantly higher than the ACL-reconstructed individuals on two of the functional outcome measures: global rating (p < 0.001) and KOS-ADLS (p < 0.001). There was no significant difference between the two groups for the CKRS – Sports Activity Scale score (p = 0.639) (Figure 3.3).
3.2.1.4 Episodes of giving way

Six of the subjects in the ACL-reconstructed group reported having one or more episodes of giving way since the surgery, while eleven had no episodes of giving way. This data was used to help categorise ACL-reconstructed individuals as copers or non-copers in part two of the study. In previous studies episodes of giving way were not defined, except to say that any episodes of giving way were documented, and was used as part of the classification of ACL-deficient subjects as copers or non-copers Eastlack et al. 1999; Snyder-Mackler et al. 1997). The episodes of giving way were not restricted to a certain period of time after the injury.

3.2.1.5 Strength

The absolute values for the quadriceps peak torque adjusted for body weight for concentric and eccentric muscle strength testing are shown in Figures 3.4 to 3.6. The absolute values for the hamstring peak torque adjusted for body weight for concentric and eccentric muscle strength testing are shown in Figures 3.7 to 3.9. There were no
significant differences in quadriceps or hamstring concentric strength at 60 or 180°/s between the involved and uninvolved limbs in the ACL-reconstructed group, and the dominant and non-dominant limbs in the control group. No significant difference was found between the involved and uninvolved limbs in the ACL-reconstructed group, and the dominant and non-dominant limbs in the control group during eccentric strength testing at 60°/s (Tables 3.2 and 3.3 show the differences in quadriceps and hamstring peak torque/body weight between the limbs for the ACL-reconstructed (ACLR) groups and the control group).

Figure 3.4 Summary of the quadriceps peak torque/body weight for concentric testing at 60°/s for the ACL-reconstruction and control groups (Nm.kg⁻¹).
Figure 3.5 Summary of the quadriceps peak torque/body weight for concentric testing at 180°/s for the ACL-reconstruction and control groups (Nm.kg⁻¹).

Figure 3.6 Summary of the quadriceps peak torque/body weight for eccentric testing at 60°/s for the ACL-reconstruction and control groups (Nm.kg⁻¹).
Table 3.2  Summary of differences in quadriceps peak torque/body weight between the legs of the ACL-reconstruction and control groups (Nm.kg⁻¹)

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Concentric 60°/s</th>
<th>n</th>
<th>Concentric 180°/s</th>
<th>n</th>
<th>Eccentric 60°/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>ACLR</td>
<td>17</td>
<td>-6.84</td>
<td>45.14</td>
<td>17</td>
<td>-7.06</td>
<td>41.02</td>
</tr>
<tr>
<td>Controls</td>
<td>10</td>
<td>4.90</td>
<td>18.05</td>
<td>10</td>
<td>-8.99</td>
<td>13.41</td>
</tr>
</tbody>
</table>

* One subject was unable to perform the eccentric strength tests even after careful instruction thus all eccentric data are reported for n = 16 subjects.

All values are the difference between the uninvolved and involved limb in the ACLR group and the dominant and non-dominant limbs in the control group. Negative values in the ACLR group indicate that the reconstructed limb was stronger than the uninvolved limb. Negative values in the control group indicate that the non-dominant limb was stronger than the dominant limb.

Figure 3.7  Summary of the hamstring peak torque/body weight for concentric testing at 60°/s for the ACL-reconstruction and control groups (Nm.kg⁻¹).
Figure 3.8 Summary of the hamstring peak torque/body weight for concentric testing at 180°/s for the ACL-reconstruction and control groups (Nm.kg⁻¹).

Figure 3.9 Summary of the hamstring peak torque/body weight for eccentric testing at 60°/s for the ACL-reconstruction and control groups (Nm.kg⁻¹).
Table 3.3 Summary of differences in hamstring peak torque/body weight between the legs of the ACL-reconstructed and control groups (Nm.kg^-1)

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Concentric 60°/s</th>
<th>n</th>
<th>Concentric 180°/s</th>
<th>n</th>
<th>Eccentric 60°/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>ACLR</td>
<td>17</td>
<td>-0.85</td>
<td>21.44</td>
<td></td>
<td>17</td>
<td>0.02</td>
</tr>
<tr>
<td>Controls</td>
<td>10</td>
<td>-5.15</td>
<td>14.37</td>
<td></td>
<td>10</td>
<td>-8.54</td>
</tr>
</tbody>
</table>

* One subject was unable to perform the eccentric strength tests even after careful instruction thus all eccentric data are reported for n = 16 subjects.

All values are the difference between the uninvolved and involved limb in the ACLR group and the dominant and non-dominant limbs in the control group. Negative values in the ACLR group indicate that the reconstructed limb was stronger than the uninvolved limb. Negative values in the control group indicate that the non-dominant limb was stronger than the dominant limb.

3.2.1.6 Time-to-Peak Torque

The absolute values for the quadriceps time to peak torque for concentric and eccentric muscle strength testing are shown in Figures 3.10 to 3.12. The absolute values for the hamstring time to peak torque for concentric and eccentric muscle strength testing are shown in Figures 3.13 to 3.15. The time needed to reach peak torque for the hamstring muscle of the involved limb during the concentric strength testing at 180°/s was significantly faster in the ACL-reconstructed group compared to the control group (55.29 versus -98.0 ms; p < 0.04) (Figure 3.14). The negative value in the ACLR group indicates that the involved limb score was slower than the uninvolved limb. The time needed to reach peak torque of the hamstring muscle of the involved limb during eccentric testing at 60°/s was significantly slower in the ACL-reconstructed group compared to the control group (-0.62 versus 362.00 ms; p < 0.05) (Figure 3.15, Table 3.4).
Figure 3.10 Summary of the quadriceps time to peak torque for concentric testing at 60°/s for the ACL-reconstruction and control groups (ms).

Figure 3.11 Summary of the quadriceps time to peak torque for concentric testing at 180°/s for the ACL-reconstruction and control groups (ms).
Figure 3.12 Summary of the quadriceps time to peak torque for eccentric testing at 60°/s for the ACL-reconstruction and control groups (ms).

Figure 3.13 Summary of the hamstring time to peak torque for concentric testing at 60°/s for the ACL-reconstruction and control groups (ms).
Figure 3.14 Summary of the hamstring time to peak torque for concentric testing at 180°/s for the ACL-reconstruction and control groups (ms).
* $p < 0.04$

Figure 3.15 Summary of the hamstring time to peak torque for eccentric testing at 60°/s for the ACL-reconstruction and control groups (ms).
* $p < 0.05$
Table 3.4  Summary of differences in time to peak torque between limbs in ACL-reconstructed and control groups (ms).

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Group</th>
<th>n</th>
<th>Concentric 60% n</th>
<th>Concentric 180% n</th>
<th>Eccentric 60% n</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean  SD</td>
<td>Mean  SD</td>
<td>Mean  SD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quadriceps</td>
<td>ACLR</td>
<td>17</td>
<td>97.64 138.72</td>
<td>17 -7.06 115.85</td>
<td>16* 183.75 388.41</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>10</td>
<td>39.00 122.24</td>
<td>10 46.00 65.35</td>
<td>10 579.00 619.25</td>
</tr>
<tr>
<td>Hamstrings</td>
<td>ACLR</td>
<td>17</td>
<td>241.76 318.20</td>
<td>17 55.29 175.75</td>
<td>16* -0.62 299.31#</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>10</td>
<td>83.00 322.11</td>
<td>10 -98.0 146.80</td>
<td>10 362.00 581.97</td>
</tr>
</tbody>
</table>

* One subject was unable to perform the eccentric strength tests even after careful instruction thus all eccentric data are reported for n = 16 subjects.

All values are the difference between the uninvolved and involved limb in the ACLR group and the dominant and non-dominant limbs in the control group. Negative value in the ACLR group indicates that the involved limb was faster than the uninvolved limb. Negative value in the control group indicates that the non-dominant limb was than the dominant limb.

† p = 0.03

# p < 0.05

3.2.1.7 Functional hop tests

There were no significant differences between the involved and uninvolved limbs in the ACL-reconstructed group, and the dominant and non-dominant limbs in the control group during performance of all four hop tests (Table 3.5).

Table 3.5  Summary of differences between limbs of the ACLR and control groups during four functional hop tests

<table>
<thead>
<tr>
<th>n</th>
<th>6-meter timed hop (s)</th>
<th>Cross-over hop (cm)</th>
<th>3-meter hop (cm)</th>
<th>Single hop (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean  SD</td>
<td>Mean  SD</td>
<td>Mean  SD</td>
<td>Mean  SD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>17</td>
<td>0.32 1.29</td>
<td>0.07 0.45</td>
<td>-0.08 0.43</td>
</tr>
<tr>
<td>Controls</td>
<td>10</td>
<td>0.04 0.16</td>
<td>0.004 0.27</td>
<td>0.06 0.19</td>
</tr>
</tbody>
</table>

All values are mean ± SD. Negative values in the ACLR group indicates that the involved limb score was higher than the uninvolved limb. Negative values in the control group indicate that the non-dominant limb scored higher than the dominant limb.

3.2.1.8 EMG data

There were no significant differences in the EMG data between the involved and uninvolved limbs of the ACL-reconstructed group and the dominant and non-dominant
control group for any of the muscle groups (VMO, VLO, ST and BF) for concentric testing at either 60 or 180°/s (figure 3.16 and 3.17). During the concentric testing at both 60° and 180°/s some of the EMG data was excluded due to interference or unusable data. Table 3.6 summarises the available data for each channel.

<table>
<thead>
<tr>
<th>Muscle group</th>
<th>Testing at 60°/s</th>
<th>Testing at 180°/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Subjects (n=17)</td>
<td>Controls (n=10)</td>
</tr>
<tr>
<td>VMO</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>VLO</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>ST</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>BF</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 3.16 Summary of the EMG data of the various muscle groups for concentric testing at 60°/s. All values are differences between the uninvolved and involved limbs in the ACLR group, and the dominant and non-dominant limbs in the control group. Negative values in the ACLR group indicate that the involved limb had greater EMG activity than the uninvolved limb. Negative values in the control group indicate that the non-dominant limb had greater EMG activity than the dominant limb.
3.2.1.9 Time of onset of VMO and VL during the step up/down test

During the step up/down test some of the EMG data was excluded due to interference or unusable data (Table 3.6). There was no significant difference in the time of onset of VMO muscle activity relative to the VL, as determined by visual assessment and expressed as the difference in the time of onset of EMG activity between the VMO and VL, between the involved limb of the ACL-reconstruction and the non-dominant limb of the control groups during the step up or step down phase of the functional test (figure 3.18).
Figure 3.18 Summary of the time of onset of the VMO in relation to the VL during the step up/step down test between the involved limb of the ACL-reconstruction and the non-dominant limb of the control groups. Negative value in the ACLR group indicates that the involved limb’s VL was slower than the VMO.

Although not significant, in the involved limb of the ACL-reconstructed group the VMO was activated before the VL during both the step up and step down phase of the test. The VL was activated before the VMO muscle during both phases in the non-dominant limb of the control group.

3.2.2 Comparing ‘copers’ to ‘non-copers’ within ACL-reconstructed group

Using the criteria describes in section 3.1.15, seven subjects could be classified as copers (4 men and 3 women; mean age = 24.9 years, SD = 6.2) while ten subjects could be classified as non-copers (6 men and 4 women; mean age = 33.5 years, SD = 10.0) (Table 3.7).
Table 3.7. Classification of subjects as coper or non-coper.

<table>
<thead>
<tr>
<th>Subject number</th>
<th>KOS *</th>
<th>Global rating score *</th>
<th>Timed hop *</th>
<th>Episodes of giving way†</th>
<th>Coper (1)</th>
<th>Non-coper (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>2</td>
<td>2</td>
</tr>
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<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
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</tr>
<tr>
<td>5</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
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<td>1</td>
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<td>1</td>
<td>1</td>
<td>1</td>
</tr>
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<td>13</td>
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<td>2</td>
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<td>2</td>
</tr>
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<td>14</td>
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<td>1</td>
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<td>1</td>
<td>1</td>
<td>1</td>
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<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

* Group 1 ≥ 90%; Group 2 < 90%
† Group 1 = 0 (no episodes of giving way); Group 2 = one or more episodes of giving way

The anthropometrical data for the copers and non-copers are reported in Table 3.8. There was no significant difference between the limbs of the two groups when measured for age, body mass, height and differences in lean thigh volume between limbs (figure 3.19).

Table 3.8 Anthropometrical data of copers and non-copers.

<table>
<thead>
<tr>
<th>Group</th>
<th>n</th>
<th>Age (years)</th>
<th>Body mass (kg)</th>
<th>Body height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>SD</td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Age</td>
<td>Body mass</td>
<td>Body height</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SD</td>
<td></td>
</tr>
<tr>
<td>Copers</td>
<td>7</td>
<td>24.9</td>
<td>6.1</td>
<td>78.09</td>
</tr>
<tr>
<td>Non-copers</td>
<td>10</td>
<td>33.5</td>
<td>10.0</td>
<td>71.67</td>
</tr>
</tbody>
</table>
Figure 3.19 Differences in lean thigh volume (cm$^3$) between limbs for the copers and non-copers (p=0.209). All values are differences between the ACL-reconstructed and uninjured limbs in the coper and non-coper groups. A positive value indicates that the uninjured limb score was higher than the involved limb.

3.2.2.1 Self-reported measures of knee function

The copers scored significantly higher in the self-reported measures of function: KOS-ADLS (p = 0.02) and GRS (p = 0.005). The CSAS, although not significant, also showed a trend towards a higher score for the copers (p = 0.053) (Figure 3.20).

Figure 3.20 Comparison of the self-reported outcome measures between coper and non-coper groups: global rating score (GRS) (* p < 0.005), Knee Outcome Survey – Activities of Daily Living Scale (KOS – ADLS) (# p < 0.02) and Cincinnati Knee Rating Scale – Sports Activity Scale (CKRS – CSAS) (p = 0.053).
3.2.2.2 Strength

The absolute values for the quadriceps peak torque adjusted for body weight for concentric and eccentric muscle strength testing are shown in Figures 3.21 to 3.23. The absolute values for the hamstring peak torque adjusted for body weight for concentric and eccentric muscle strength testing are shown in Figures 3.24 to 3.26. There was no significant difference between the copers and non-copers for the quadriceps and hamstring muscles for both the concentric and eccentric muscle strength testing (Table 3.9 and 3.10).

![Chart of peak torque adjusted for body weight](chart.png)

Figure 3.21 Summary of the quadriceps peak torque/body weight for concentric testing at 60°/s for the coper and non-coper groups (Nm.kg⁻¹).
Figure 3.22 Summary of the quadriceps peak torque/body weight for concentric testing at 180°/s for the coper and non-coper groups (Nm.kg⁻¹).

Figure 3.23 Summary of the quadriceps peak torque/body weight for eccentric testing at 60°/s for the coper and non-coper groups (Nm.kg⁻¹).

Table 3.9 Summary of differences in quadriceps peak torque/body weight between the copers and non-copers (Nm.kg⁻¹)

<table>
<thead>
<tr>
<th>Group</th>
<th>n</th>
<th>Concentric 60°/s</th>
<th>n</th>
<th>Concentric 180°/s</th>
<th>n</th>
<th>Eccentric 60°/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean  SD</td>
<td></td>
<td>Mean  SD</td>
<td></td>
<td>Mean  SD</td>
</tr>
<tr>
<td>Copers</td>
<td>7</td>
<td>-17.20 40.04</td>
<td>7</td>
<td>-14.91 35.33</td>
<td>7</td>
<td>25.56 47.69</td>
</tr>
<tr>
<td>Non-copers</td>
<td>10</td>
<td>0.42   49.11</td>
<td>10</td>
<td>-1.56 45.57</td>
<td>9*</td>
<td>22.79 60.02</td>
</tr>
</tbody>
</table>

* One non-coper was unable to perform the eccentric strength tests even after careful instruction thus all eccentric data are reported for n = 9 in the non-coper group. Negative value indicates that the involved limb was stronger than the uninvolved limb.
Figure 3.24 Summary of the hamstring peak torque/body weight for concentric testing at 60°/s for the coper and non-coper groups (Nm.kg⁻¹).

Figure 3.25 Summary of the hamstring peak torque/body weight for concentric testing at 180°/s for the coper and non-coper groups (Nm.kg⁻¹).
Figure 3.26 Summary of the hamstring peak torque/body weight for eccentric testing at 60°/s for the coper and non-coper groups (Nm.kg⁻¹).

Table 3.10 Summary of differences in hamstrings peak torque/body weight between the copers and non-copers (Nm.kg⁻¹)

<table>
<thead>
<tr>
<th>Group</th>
<th>n</th>
<th>Concentric 60°/s</th>
<th></th>
<th>Concentric 180°/s</th>
<th></th>
<th>Eccentric 60°/s</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Copers</td>
<td>7</td>
<td>-4.80</td>
<td>28.77</td>
<td>7</td>
<td>-4.83</td>
<td>16.13</td>
<td>7</td>
</tr>
<tr>
<td>Non-copers</td>
<td>10</td>
<td>1.92</td>
<td>15.65</td>
<td>10</td>
<td>3.41</td>
<td>26.21</td>
<td>9</td>
</tr>
</tbody>
</table>

* One non-coper was unable to perform the eccentric strength tests even after careful instruction thus all eccentric data are reported for n = 9 in the non-coper group. Negative value indicates that the involved limb was stronger than the uninvolved limb.

3.2.2.3 Time-to-Peak Torque

The absolute values for the quadriceps time to peak torque for concentric and eccentric muscle strength testing are shown in Figures 3.27 to 3.29. The absolute values for the hamstring time to peak torque for concentric and eccentric muscle strength testing are shown in Figures 3.30 to 3.32. In the present study there was no significant difference between the copers and non-copers for the time to reach peak torque for either the quadriceps or hamstring muscles during isokinetic testing (Table 3.11).
Figure 3.27 Summary of the quadriceps time to peak torque for concentric testing at 60°/s for the coper and non-coper groups (ms).

Figure 3.28 Summary of the quadriceps time to peak torque for concentric testing at 180°/s for the coper and non-coper groups (ms).
Figure 3.29 Summary of the quadriceps time to peak torque for eccentric testing at 60°/s for the coper and non-coper groups (ms).

Figure 3.30 Summary of the hamstring time to peak torque for concentric testing at 60°/s for the coper and non-coper groups (ms).
Figure 3.31 Summary of the hamstring time to peak torque for concentric testing at 180°/s for the coper and non-coper groups (ms).

Figure 3.32 Summary of the hamstring time to peak torque for eccentric testing at 60°/s for the coper and non-coper groups (ms).
Table 3.11 Summary of differences in time to peak torque between limbs in the coper and non-coper groups (ms).

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Group</th>
<th>n</th>
<th>Concentric 60°/s</th>
<th>n</th>
<th>Concentric 180°/s</th>
<th>n</th>
<th>Eccentric 60°/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Quadriceps</td>
<td>Copers</td>
<td>7</td>
<td>72.86</td>
<td>165.30</td>
<td>7</td>
<td>-2.86</td>
<td>38.17</td>
</tr>
<tr>
<td></td>
<td>Noncopers</td>
<td>10</td>
<td>119.00</td>
<td>118.93</td>
<td>10</td>
<td>-16.00</td>
<td>150.64</td>
</tr>
<tr>
<td>Hamstrings</td>
<td>Copers</td>
<td>7</td>
<td>130.00</td>
<td>273.74</td>
<td>7</td>
<td>72.86</td>
<td>101.28</td>
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<td></td>
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<td>358.00</td>
<td>291.39</td>
<td>10</td>
<td>41.00</td>
<td>218.77</td>
</tr>
</tbody>
</table>

* One subject was unable to perform the eccentric strength tests even after careful instruction thus all eccentric data are reported for n = 16 subjects.

Negative value indicates that the reconstructed limb score was faster than the uninvolved limb.

3.2.2.4 Functional hop tests

There was no significant difference between the copers and non-copers for any of the functional hop tests (Table 3.12).

Table 3.12 Summary of differences between limbs of the coper and non-coper groups during four functional hop tests

<table>
<thead>
<tr>
<th>n 6-meter timed hop (s)</th>
<th>Cross-over hop (cm)</th>
<th>3-meter hop (cm)</th>
<th>Single hop (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Copers</td>
<td>7</td>
<td>-0.01</td>
<td>0.24</td>
</tr>
<tr>
<td>Non-copers</td>
<td>10</td>
<td>-0.55</td>
<td>1.68</td>
</tr>
</tbody>
</table>

Negative value indicates that the involved limb scored higher than the uninvolved limb.

3.2.2.5 EMG

During the concentric testing at both 60 and 180°/s some of the EMG data was excluded due to interference of the channels (Table 3.13). There were no significant differences in the EMG data between the ACL-reconstructed and uninjured limbs of the coper and non-copers groups for any of the muscle groups (VMO, VLO, ST and BF) for concentric testing at either 60 or 180°/s (figure 3.33 and 3.34).
Table 3.13 Summary of number of EMG channels available for use during statistical analysis.

<table>
<thead>
<tr>
<th>Muscle group</th>
<th>Testing at 60°/s</th>
<th></th>
<th>Testing at 180°/s</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Copers (n=7)</td>
<td>Non-copers (n=10)</td>
<td>Copers (n=7)</td>
<td>Non-copers (n=10)</td>
</tr>
<tr>
<td>VMO</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>VLO</td>
<td>4</td>
<td>7</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>ST</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>BF</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 3.33 Summary of the differences between limbs of the EMG data of the various muscle groups for concentric testing at 60°/s. All values are differences between the ACL-reconstructed and uninjured limbs in the coper and non-coper groups. A negative value indicates that the involved limb had greater EMG activity than the uninjured limb.
Figure 3.34 Summary of the differences between limbs of the EMG data of the various muscle groups for concentric testing at 180°/s. All values are differences between the ACL-reconstructed and uninjured limbs in the coper and non-coper groups. Negative value indicates that the involved limb had greater EMG activity than the uninvolved limb. Note: for the BF muscle there was only one subject’s data available for the copers, therefore there was no standard deviation for this group.

### 3.2.2.6 Time of onset of VMO and VL during the step up/down test

During the step up/down test some of the EMG data was excluded due to interference or unusable data (Table 3.13). There was no significant difference in the time of onset of VMO muscle activity relative to the VL, as determined by visual assessment and expressed as the difference in the time of onset of EMG activity between the VMO and VL, between the involved limb of the coper and non-coper groups during the step up or step down phase of the functional test (Figure 3.35).
Figure 3.35 Summary of the time of onset of the VMO in relation to the VL during the step up/step down test in the involved limb of the coper and non-coper groups. Negative value indicates that the VL time of onset was slower than the VMO time of onset.

3.3 Discussion

Comparing the ACL-reconstructed group to control group

The ACL-reconstructed group and control group were similar for age, sport participation levels, KT-1000 measure of anterior laxity, body mass, height and LTV. A study by Feller et al (2004) found that patients who attended physiotherapy on a very limited basis after ACL reconstruction achieved the same outcomes as patients who attended regular physiotherapy rehabilitation sessions. This may indicate that the long term outcomes of patients after ACL reconstruction is independent of specific physiotherapy input.

The control group scored significantly higher in their self-reported measures of knee function compared to the ACL-reconstructed group. Even though the subjects who had
undergone ACL-reconstruction scored lower in these subjective measures (KOS-ADLS p < 0.001; GRS p < 0.0003), they all returned to level I or II sport activities. Wojtys and Huston (2000) reported that 20 of 25 subjects (80%), who underwent an ACL-reconstruction using patellar tendon graft, subjectively reported that they had returned to their pre-injury levels of function despite the fact that muscle function in most of the subjects was not restored to normal levels. However, Kvist et al (2005) observed that patients who had undergone ACL-reconstruction often display a lack of confidence or decreased perceived function in the involved limb despite an improvement of subjective and objective stability following surgery. These results support the findings of the present study where the subjects in the ACL-reconstructed group were very similar to the control group for objective outcome measures of strength, functional hop tests and EMG data, although they scored lower on their self-reported measures of knee function. These results may indicate that psychological factors could influence the perceived functional outcome even two to five years following ACL-reconstruction.

In the present study there were no significant differences in the strength between the limbs of the subjects and controls during concentric and eccentric muscle strength testing. Persistent quadriceps weakness following ACL injury (Noyes et al. 1991; St Clair Gibson et al. 2000a) and ACL-reconstruction (Novak et al. 1996; Wojtys & Huston 2000; Keays et al. 2001; Beard et al. 2001; Jarvela et al. 2002) has been reported in the literature. St Clair Gibson et al (2000b) reported no significant difference in isokinetic quadriceps strength deficit between ACL-deficient and ACL-reconstructed groups indicating that the ACL-reconstruction does not necessarily improve muscle strength. Despite this persistent quadriceps muscle strength impairment, St Clair Gibson et al (2000b) reported an
improvement in functional ability following ACL-reconstruction. However, in the present study the ACL-reconstructed individuals scored significantly lower in their perceived functional outcome, despite the lack of any significant muscle strength deficit compared to the control groups, and the fact that subjects have returned successfully to their sporting activities (all regularly participate in Level I or II sport activities).

There were no significant differences between the two groups for any of the four hop tests used as functional outcome measures. Keays et al (2001) reported that the functional hop tests improved following ACL-reconstruction using semitendinosus/gracilis quadruple stranded graft. Noyes et al (1991) demonstrated no significant relationship between functional hop tests and KT-1000 arthrometer test results, isokinetic testing of the quadriceps and hamstring muscles, symptoms reported and self-assessed function in subjects with ACL-deficient knees. In a study investigating knee kinematics and kinetics following ACL-reconstruction, Bush-Joseph et al (2001) found functional adaptations during higher-demand activities (measured by jogging, jog and cut, jog and stop) in a group of individuals who underwent ACL-reconstruction using PT graft. During the more demanding activities the peak external flexion moment was significantly decreased and the peak external extension moment was significantly increased in the ACL-reconstructed group. These adaptations occurred although there were no statistically significant differences between the ACL-reconstructed subjects and the controls for isokinetic quadriceps or hamstrings strength (Bush-Joseph et al. 2001). In the present study the functional outcome of the ACL-reconstructed group, as measured by the four hop tests, were comparable to that of the control group. However, the kinetics and kinematics of the hop tests were not investigated.
In the present study there were no significant differences between the ACL-reconstructed and control groups for timing of onset of VMO muscle activity in relation to VL and EMG data. In contrast, the time to reach peak torque of the hamstring muscle in the involved limb during concentric strength testing at 180°/s was significantly faster in the ACL-reconstructed group compared to the control group. Wojtys and Huston (2000) used the time to peak force during muscle contraction as a measure of neuromuscular function. They found that muscle timing and recruitment order were altered following ACL injury that persisted even 12 to 18 months following ACL-reconstruction. Their study reported that the time to reach peak torque of the hamstring was significantly slower in the ACL-deficient limb compared to the uninjured limb of the subjects. After the subjects underwent ACL-reconstruction using a patellar tendon autograft the difference in time to reach peak torque improved, and after 18 months the hamstring of the ACL-reconstructed limb performed better than the contralateral limb. The study did not compare the results to that of a control group.

In contrast to the concentric results at 180°/s testing, in the present study the time to reach peak torque of the hamstring muscle in the involved limb during eccentric testing at 60°/s was significantly slower in the ACL-reconstructed group compared to the control group. Studies have found that the hamstring muscles act as a synergist to the ACL, and following ACL injury and reconstruction increased hamstring activity may help to prevent anterior tibial translation (Solomonow et al. 1987; St Clair Gibson 2002). The adaptations in hamstring function at different speeds found in the present study could therefore be a centrally controlled mechanism to help protect the graft following ACL-
reconstruction, by preventing excessive anterior translation or it could be a maladaptation as a result of the injury.

These results seem to indicate that ACL-reconstruction using semitendinosus/gracilis double-strand graft delivers satisfactory outcome for measures of neuromuscular function, such as muscle strength, functional performance and muscle activity. The significant difference in time to reach peak torque for the hamstring muscle between the limbs of the ACL-reconstructed and control groups that was found in the present study may be a ‘protective’ mechanism or at least an alteration caused by the injury. However, the lack of significant difference between the ACL-reconstructed and control groups for any of the objective outcome measures do not correlate with the lower self-reported function in the ACL-reconstruction groups. This suggests that perceived functional outcome following ACL-reconstruction surgery may depend on more than physical characteristics. Further research is also indicated to investigate the role that psychological factors may have on outcome measures.

Comparing ‘coper’ group to ‘non-coper’ group within ACL-reconstructed group

The coper and non-coper populations in the present study were similar for body mass, height, LTV and sport participation levels. Although there was no significant difference between the coper and non-coper groups for age, the non-copers were older than the copers (p = 0.06). It could be that younger people cope better to injury, or with the stress associated with injury. However, in their study Eastlack et al (1999) found that the copers were older than the ‘subacute’ and ‘chronic’ non-copers (30 versus 23 and 28).
There was no significant difference in the ligament laxity score as measured by the KT-1000 arthrometer between the coper and non-coper groups. Eastlack et al (1999) also reported no significant difference in ligament laxity between copers and non-copers following ACL injury. In fact, in some of the cases in their study the copers displayed a greater laxity measurement. In the present study, the main difference between the copers and non-copers was in self-reported function, which could indicate that ligament laxity is not related to functional ability.

In the present study self-reported measures of knee function (KOS and GRS) were used to help classify ACL-reconstructed individuals as copers or non-copers. Eastlack et al (1999) found a significant difference in the subjective measures between the copers and non-copers in their study of ACL-injured individuals: GRS (p < 0.01) and KOS-Sport (p < 0.001). The authors concluded that the GRS and the KOS scores were the best method to differentiate between copers and non-copers in an ACL-injured population. In the present study no significant differences were found between the copers and non-copers for any of the objective outcome measures—strength, functional hop tests, and EMG data. The criteria used in this study to classify individuals as copers or non-copers were based on studies on ACL-deficient individuals. This may indicate that following ACL-reconstruction the classification criteria used to distinguish between copers and non-copers may need to be more sensitive to detect differences in objective outcome measures between the two groups. The lack of any differences in objective outcome measures may be suggestive of a psychological cause for the perceived functional ability of the ACL populations.
Although the coper and non-coper groups demonstrated no significant differences for isokinetic quadriceps and hamstring muscle strength, the quadriceps on the involved side of the copers tended to be stronger than the uninvolved side during concentric strength testing at both 60 and 180°/s. In their study on the movement patterns in copers and non-copers following ACL-injury, Rudolph et al. (1998) found that the coper group demonstrated a greater quadriceps muscle strength. However, this difference was not significant and could not explain the successful compensation of the copers. In a study comparing copers with non-copers in ACL-injured individuals Eastlack et al. (1999) found a significant difference in quadriceps muscle strength, as measure by maximum voluntary isometric contraction using the burst superimposed technique, between the copers and non-copers. Copers also scored significantly better in the four hop tests than non-copers. Both these studies (Rudolph et al. 1998; Eastlack et al. 1999) investigated functional status following ACL injury. To our knowledge, there have been no research to compare copers with non-copers following ACL-reconstruction.

In the present study there were no significant differences between the coper and non-coper groups for time to reach peak torque, functional hop tests and EMG measures of muscle activity in the VMO, VL, ST and BF muscles. From the above findings it is evident that even though the two groups demonstrate significant differences for the self-reported measures of knee function, there are no differences in the objective measures between the two groups. Several explanations for this lack of difference between the copers and non-copers must be considered. First the subjects were divided into coper and non-coper groups based on research performed on ACL-injured individuals (Eastlack et al. 1999; Fitzgerald et al. 2000) and that the conclusions drawn from these studies may
not apply to ACL-reconstructed individuals. Secondly, it may be that following ACL-reconstruction the differences between copers and non-copers is more subtle and measures used in the current classification is not sensitive enough to detect the differences. Thirdly, following ACL-reconstruction self-reported measures of knee function may not by the best method to classify subjects as copers or non-copers and the classification proposed by Eastlack et al (1999) is insufficient for the ACL-reconstructed population. Nyland et al (2002) found that ACL-deficient individuals with perceived functional deficits displayed a greater external health locus of control. This suggests that the difference between copers and non-copers could be influenced by psychological factors, and that could explain why the only differences between the copers and non-copers are found in self-reported measures of knee function.

Past studies on copers and non-copers were all performed on ACL-deficient subjects (Eastlack et al. 1999; Alkjaer et al. 2003; Rudolph et al. 1998). Part of the classification of non-copers was that these individuals required surgical stabilisation. It may be that following ACL-reconstruction the definition of individuals as copers or non-copers becomes irrelevant. In cases where surgeons perform ACL-reconstruction during the acute phase (< 6 weeks following the original injury) individuals may not have been able to 'develop' into copers or non-copers.

The present study adapted the classification proposed by Eastlack et al (1999) to compare copers from non-copers following ACL-reconstruction. Future research could identify subjects as copers and non-copers pre-construction and follow them prospectively to measure neuromuscular performance following ACL-reconstruction. The main problem
with this proposed research is that individuals who are identified as copers may have a seemingly inherent strategy to cope successfully with their injury and may not require surgery. The role psychological factors may have on an athlete’s perceived functional ability or the physical outcome following ACL-reconstruction should also be further investigated. It is possible that a person’s pre-existing personality profile will decide what their subjective outcome will be.

3.4 Limitations of study
A limitation of the study was the relatively small final sample size of the subjects that could lead to Type 1 error. There was also an imbalance between the male: female ratio of the subject and control groups. Although this difference was not statistically significant future studies should perhaps control better for gender. Furthermore the control group was small compared to the ACL-reconstructed group. This may lead to the group not being truly representative. Future studies should aim to recruit a control group of equal size to the experimental group and should include power analysis for both groups.

Another limitation of the study was that it was not possible to control for differences in rehabilitation programs among subjects. This was not possible as the present study was a retrospective study. Following the ACL-reconstruction the subjects did not partake in a controlled standardised rehabilitation program. Even though there is evidence from the literature that specific rehabilitation programmes do not affect outcome, future studies should control for this as a confounding variable.
In four of the subjects who underwent ACL reconstruction, additional procedures were performed at the time of the surgery: three had meniscal repairs and one subject had a lateral collateral ligament repair. This may have affected the homogeneity of the ACL-reconstructed group and future studies should try and address this.

Limitations in the method of testing existed. Firstly the present study is a cross-sectional study – it is only a picture in one point in time. A study that follows copers and non-copers from before surgery and compares their outcome measures pre-operatively to their post-operative outcome measures may answer some of the questions raised by the present study. Secondly the subjects in the study did not undergo a familiarization period, in the form of a prior complete test, on the Biodex machine used during the isokinetic muscle testing. During the isometric muscle strength testing fear or pain could affect the outcome. To control for this the subject was instructed to stop the testing if they experienced any pain and each subject underwent a three practise trials to familiarise themselves with the test before commencing the testing. Thirdly kinetic and kinematic data were not collected and the effect of the muscle activation on movement patterns is thus unknown. A foot switch was not used during the step up/down tests and the onset of EMG activity during the test was determined using visual examination. Although this method has been found to be repeatable between testing days, the onset of EMG data by visual determination varied significantly from the majority of computer-based methods (Hodges & Bui 1996). A marked number of EMG channels were excluded due to interference or broken leads. This may limit the validity of the data on EMG activity following ACL reconstruction. In future studies greater care should be taken to ensure that EMG equipment is functioning correctly.
The classification used in previous studies was changed for the purpose of the present study to accommodate the improvement in function following ACL-reconstruction. Changing the classification from that already present in the literature makes comparison to previous studies difficult. Future studies could attempt keep the original classification and use a larger sample to detect differences between the copers and non-copers.

The functional stability status (coper versus non-coper) of the subjects was determined following surgery as part of this cross-sectional study. This may be an artificial classification, and future studies should aim to identify subjects as copers or non-copers and follow their neuromuscular outcome prospectively. Finally, the findings of the present study are limited to subjects who had undergone ACL-reconstruction using a double-strand semitendinosus/gracilis graft only.

3.5 Future research

Future research should aim to ascertain whether individuals who had undergone ACL-reconstruction can be classified as copers and non-copers by doing a prospective study, and, if this is the case, try to develop a classification system based on their neuromuscular control, performance, or psychological make-up. The potential ability to classify individuals according to their functional outcome may help to identify the underlying neuromuscular mechanisms responsible for these individual differences in outcome following ACL-reconstruction and could help focus future rehabilitation to ensure athletes can return to their sport sooner and decrease recurrence of injury. Future research should also investigate the effects psychological factors and personality profile may have
on an athlete’s perceived functional ability or physical outcome following ACL-reconstruction.

3.6 Conclusion

From the first part of this study it is evident that the physical outcome of the ACL-reconstruction using the semitendinosus/gracilis two-stranded graft is comparable to the function of a control group for strength, functional hop tests and EMG data, despite subjects in the ACL-reconstruction group subjectively rating their knee function as impaired compared to the control group.

The difference in time to reach peak torque between the legs for the hamstring muscle during the concentric strength testing at $180^\circ$/s was significantly faster in the ACL-reconstructed group compared to the control group. The difference between limbs in time needed to reach peak torque of the hamstring muscle during eccentric testing at $60^\circ$/s was significantly slower in the ACL-reconstructed group compared to the control group. These changes could be an adaptation following the ACL injury, which persists despite surgical stabilisation, as a protection mechanism to protect the knee joint during dynamic activity.

It would be interesting to compare the results of the present study with the findings of Wojtys and Huston (2002) of comparing the time to reach peak torque of the hamstring muscle of the involved compared to uninvolved limb, as opposed to the controls. However we felt that this comparison would not contribute to the present paper since this
was not one of the aims that the study set out to investigate but could be considered for future research.

In the second part of the present study the individuals who had undergone ACL-reconstruction were divided into two groups based on their KOS-ADLS score, global rating score, timed hop test score and their number of reported episodes of giving way. There were more non-copers than copers using this classification system. There were no differences between the copers and non-copers for strength, functional hop tests or EMG data.

Further research is indicated to determine whether inherent differences in dynamic stabilisation strategies continue to exist following surgical stabilisation, and what the best criteria is to help classify individuals as copers or non-copers following ACL-reconstruction. There is also a need for further investigation into how psychological factors could affect perceived functional outcome following ACL-reconstruction, since this could influence the outcome of rehabilitation.
Chapter 4

Summary and conclusion

Recent studies have identified that individuals display inherent differences in functional ability following ACL-injury. A classification system has previously been developed to categorise individuals with ACL injury as either ‘copers’ or ‘non-copers’. These differences in coping strategies were used to group individuals and correlate these groups to different outcome measures, such as ligament laxity, muscle strength and movement patterns. These studies aimed to identify the underlying neuromuscular mechanism responsible for these differences in coping strategies. No studies have investigated whether there are any differences in neuromuscular performance between copers and non-copers following ACL-reconstruction.

The first part of the present study compared subjects who underwent ACL-reconstruction using two-strand semitendinosus/gracilis graft to a control group of healthy, uninjured individuals. There were no significant differences between the two groups for age, height, weight and sport participation levels. The ACL-reconstruction group performed significantly worse on the self-reported functional outcome measures: GRS, KOS-ADLS and CKRS. However, there were no differences between the ACL-reconstruction and control groups for isokinetic quadriceps and hamstring muscle strength, functional hop tests and EMG measures of muscle activity in the VMO, VL, ST and BF muscles. This suggests that the neuromuscular outcome following ACL-reconstruction using a double-strand semitendinosus/gracilis graft produces physical results comparable to that of normal age and sport-matched individuals. However, there appears to be an inconsistency between perceived functional outcome and the objective
outcome measures following ACL-reconstruction. This suggests that psychological factors may have an influence on the subjective outcome of individuals who undergoes ACL-reconstruction, and this may be an important issue to address during the rehabilitation.

In the present study, the difference in time to reach peak torque between the legs for the hamstring muscle during the concentric strength testing at 180°/s was significantly faster in the ACL-reconstructed group compared to the control group. Furthermore, the difference between limbs in time needed to reach peak torque of the hamstring muscle during eccentric testing at 60°/s was significantly slower in the ACL-reconstructed group compared to the control group. The hamstring muscle is an important synergist to the ACL, and this change in hamstring activity could indicate a centrally controlled mechanism to help protect the knee joint and the graft during dynamic activity; or a maladaptive response to the original ACL injury.

The second part of the study separated individuals who had undergone ACL reconstruction into specific ‘coper’ or ‘non-coper’ groups according to self-reported function, episodes of giving way and a functional hop test, and then correlated these groups identified with various neuromuscular outcomes to assess whether there are any significant differences in neuromuscular function between the identified groups. The classification criteria used in the study was adapted from previous studies and relies heavily on self-reported questionnaires of function. There were no significant differences for isokinetic quadriceps and hamstring muscle strength, functional hop tests and EMG measures of muscle activity in the VMO, VL, ST and BF muscles between the coper and
non-coper groups. This reinforces the possibility that the perceived functional difference between copers and non-copers could be as a result of psychological differences.

In summary, neuromuscular function and control has been suggested to play a central role in the protection of the ACL-ligament. The mechanisms underlying the differences in individuals' functional ability following ACL-injury and reconstruction have not been identified. Future research should aim to identify copers and non-copers after ACL-injury and follow them prospectively to assess the change in neuromuscular performance between the two groups in the long term. Furthermore, future research is indicated to investigate whether psychological aspects may influence objective outcome measures following ACL-reconstruction.
References


Appendices

Appendix 1 – Ethics Approval Letter

UNIVERSITY OF CAPE TOWN

Health Sciences Faculty
Research Ethics Committee
Room E53-24 Groote Schuur Hospital Old Main Building
Observatory 7725
Telephone: (021) 862 2318 • Facsimile: (021) 609 6417
email: pyscho/Sappendices/HSF

02 December 2004

REC REF: 415/2004

Ms Elsje de Villiers
202 Rozenhof
155 Dorp Street
Stellenbosch
7600

Dear Ms de Villiers

PROJECT TITLE: NEUROMUSCULAR CONTROL AND PERFORMANCE AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION: ARE THERE DIFFERENT LEVELS OF COPING

Thank you for submitting your study to the Research Ethics Committee for review.

Date considered: 26 November 2004

Decision: Approved

Please quote the REC. REF in all your correspondence.

Yours sincerely

PROFESSOR T. ZABOW
CHAIRPERSON, HSF HUMAN ETHICS
Appendix 2

Telephone Recruitment Form:

'Hallo, my name is Elsje de Villiers. I am doing my Masters degree in Sports Physiotherapy at the Sports Institute in Cape Town. I received your details from Dr. Willem van der Merwe, the surgeon who performed your cruciate ligament repair in... (year). I am contacting you to enquire whether you would be willing to participate in a research study on cruciate ligament repair and muscle control and performance.' (answer yes/no/provide more information before decide....)

1. Name: ___________________________

2. Are you willing to participate in the study? Yes[ ] No[ ]

   If yes, answer Question 3.

   If no, answer Question 4.

3. Address where Subject Information and Questionnaire can be send:

   __________________________________________
   __________________________________________
   __________________________________________
   __________________________________________

4. Why are you not willing to participate in the study?

   4.1 I am not interested[ ]

   4.2 I have no time[ ]

   4.3 I have too much problems with my knee[ ]

   4.4 I cannot get to the Sports Institute in Cape Town[ ]

   4.5 Other .......

   __________________________________________
   __________________________________________
   __________________________________________
   __________________________________________
Appendix 3

MRC/UCT Research Unit for Exercise Science/Physiotherapy Division and Sports Medicine, Department of Human Biology, Faculty of Health Sciences
University of Cape Town

SUBJECT INFORMATION

STUDY: Muscle Strength and Function after Anterior Cruciate Ligament Reconstruction: Are there different levels of coping?

Thank you for agreeing to participate in this study. The aims of this study are to find out whether there is a difference in functional outcome after anterior cruciate ligament reconstruction, and if there are differences, whether there is an association between functional outcome and neuromuscular control and performance.

Program
Prior to testing days you will be required to complete a questionnaire related to knee function. This will help to rate your knee function following your operation and rehabilitation. You will be required to be available for testing at the Sport Science Institute, in Newlands, on one occasion, for approximately 3 hours.

The session will consist of a medical questionnaire and screening for any medical condition that may influence the testing procedure. You will undergo a MRI scan and a KT1000™ measurement at the Institute to check that your graft is undamaged and to exclude any other knee joint damage, which may influence the testing procedure. You will then undergo the following tests (i) a questionnaire to assess your knee function and sport participation, (ii) a global rating of your knee function, (iii) a question regarding number of episodes of giving way since your ACL-reconstruction, (iv) a series of four functional hop tests, (v) step up/step down test, (vi) a proprioception test and (vii) isokinetic muscle strength testing. Tests (iv) to (vii) will be combined with EMG measurement of muscle activity.
All the tests will be performed according to validated procedures, which will reduce the potential risk of injury to you. You will have the chance to practise each test before it is finally performed, to familiarise you to the procedure. In the unlikely event that you get injured during the testing procedure, you will have immediate access to medical assistance, free of charge, and treatment for the duration of the injury until full recovery.

The anticipated benefits of participating in the study are that you will have an MRI investigation on the condition of your graft and to exclude any damage to any other internal structures in your operated knee. After the isokinetic testing you will also be informed if there are any muscle strength deficits present in your operated knee, which could be addressed in your personal training program.

The anticipated gain of this study is to ascertain whether patients can be divided into different groups based on their stabilising strategies following surgery, and whether there are any association between stabilising strategies and neuromuscular control and performance. This may, in the future, lead to a change in treatment strategies to improve knee stability and return to sport.

Yours sincerely

Elsje de Villiers
INFORMED CONSENT:

STUDY: Muscle Strength and Function after Anterior Cruciate Ligament Reconstruction: Are there different levels of coping?

I, .......................................................................................... (name written in blocked letters)

have been fully informed about the nature of this research project (see Subject Information Sheet) and hereby give consent to act as a subject for the research.

Testing procedure:
I have read the testing procedure in the subject information sheet, and have had the opportunity to ask questions regarding the procedure from the examiner. I acknowledge that I am aware that I will be expected to attend a testing session at the Sport Science Institute in Newlands, Cape Town.

Risks:
The testing procedures will all be done according to validated procedures, which will reduce the risk of injury. However, I have been made aware of the fact that there is a small chance of injury during the testing procedures, and that medical assistance will immediately be made available to me, free of charge, if I should require it as well as for the duration of the injury until full recovery.

The University of Cape Town and its team of researchers, who are working under the mandate of the University, will be responsible for treating any adverse or untoward events arising from participation in this research study. The subjects of this study will be registered with the UCT research insurance for this group.
Privacy:
All information regarding subject information and results from testing will be kept locked away in a secure location. Data will be stored in a blinded fashion from subject information. All individual data will be treated as confidential, and subjects will in no way be identified. You will have access to your own results if you wish to do so.

I have read and understood all the information above. I have had the opportunity to ask questions and they have been answered in a satisfactory way. I understand that I am free to withdraw from the study at any given time without prejudice, and that I will not be subjected to any pressure whatsoever to remain in the trial. I understand that the data collected may be used for scientific purposes and publication in a scientific nature.

Name: | Signature: | Date:
--- | --- | ---
Subject: | | |
Researcher: | | |
Witness: | | |
Appendix 5

Physical Activity Readiness Questionnaire (PAR-Q)

Please tick the appropriate box:

1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?
   - Yes
   - No

2. Do you feel pain in your chest when you do physical activity?
   - Yes
   - No

3. In the past month, have you had chest pain when you were not doing physical activity?
   - Yes
   - No

4. Do you lose your balance because of dizziness or do you ever lose consciousness?
   - Yes
   - No

5. Do you have a bone or joint problem that could be made worse by a change in your physical activity?
   - Yes
   - No

6. Is your doctor currently prescribing drugs (for example: water pills) for your blood pressure or heart condition?
   - Yes
   - No

7. Do you know of any other reason why you should not do physical activity?
   - Yes
   - No

If yes, explain:

........................................................................................................................................
........................................................................................................................................

(American College of Sports Medicine, 2000)
Appendix 6

Personal Demographics:

Name:
I am willing to take part in the study...
I am no longer willing to take part in the study...

Date of Birth:
Age:
Gender: Male [ ] Female [ ]

Contact telephone number:
<table>
<thead>
<tr>
<th>Home:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell no:</td>
</tr>
</tbody>
</table>

Address:

Email address:

Occupation:

Current sport participation: (level and hours participated) E.g.

<table>
<thead>
<tr>
<th>Sport</th>
<th>Level</th>
<th>Hours trained/played per week</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rugby</td>
<td>Senior club level</td>
<td>4-5</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Level</th>
<th>Hours trained/played per week</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td></td>
</tr>
<tr>
<td>2)</td>
<td></td>
</tr>
<tr>
<td>3)</td>
<td></td>
</tr>
</tbody>
</table>

Dominant leg: Left [ ] Right [ ]
## Injury information:

<table>
<thead>
<tr>
<th>Affected side</th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of original injury (month/year)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanism of injury (e.g. playing sport, car accident)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Did you receive any physiotherapy before surgery? Approximately how many sessions, over how many weeks...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Operation information:

<table>
<thead>
<tr>
<th>Date of surgery (month/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Willem van der Merwe</td>
</tr>
<tr>
<td>Patellar tendon/ hamstring tendon?</td>
</tr>
<tr>
<td>Were you in a brace following the surgery? (if yes: how long?)</td>
</tr>
<tr>
<td>Physiotherapy input</td>
</tr>
<tr>
<td>- How many sessions?</td>
</tr>
<tr>
<td>- How long (months)?</td>
</tr>
<tr>
<td>At discharge, how would you have rated your knee? (%)</td>
</tr>
</tbody>
</table>

Do you wear a brace/support during sporting activities?  
Yes [ ] No [ ]

Are you allergic to elastoplast/tape?  
Yes [ ] No [ ]

Signed ........................................ Date ........................................
Appendix 7

ANTHROPOMETRICAL DATA SHEET

Age: ________

Weight: ________ kg

Height: ________ cm

Skinfolds (mm)
Anterior mid-thigh skinfold: R ________  L ________

Girths (cm):
- Sub-gluteal: R ________  L ________
- Mid-thigh: R ________  L ________
- Above knee: R ________  L ________

Height (cm):
- Sub-gluteal to knee: R ________  L ________

ANY ADDITIONAL NOTES DURING TESTING PROCEDURE:
Appendix 8

KNEE OUTCOME SURVEY

Activities of Daily Living Scale (Irrgang et al, 1998)

Instructions: The following questionnaire is designed to determine the symptoms and limitations that you experience because of your knee while you perform your usual daily activities. Please answer each question by checking the statement that best describes you over the last 1 to 2 days. For a given question, more than one of the statements may describe you, but please mark ONLY the statement that best describes you during your usual daily activities.

Symptoms

1. To what degree does pain in your knee affect your daily activity level?
   - I never have pain in my knee.
   - I have pain in my knee, but it does not affect my daily activity
   - Pain affects my activity slightly
   - Pain affects my activity moderately.
   - Pain affects my activity severely
   - Pain in my knee prevents me from performing all daily activities.

2. To what degree does grinding or grating of your knee affect your daily activity level?
   - I never have grinding or grating in my knee.
   - I have grinding or grating in my knee, but it does not affect my daily activity.
   - Grinding or grating affects my activity slightly.
   - Grinding or grating affects my activity moderately.
   - Grinding or grating affects my activity severely.
   - Grinding or grating in my knee prevents me from performing all daily activities.
3. To what degree does stiffness in your knee affect your daily activity level?
- I never have stiffness in my knee.
- I have stiffness in my knee, but it does not affect my daily activity.
- Stiffness affects my activity slightly.
- Stiffness affects my activity moderately.
- Stiffness affects my activity severely.
- Stiffness in my knee prevents me from performing all daily activities.

4. To what degree does swelling in your knee affect your daily activity level?
- I never have swelling in my knee.
- I have swelling in my knee, but it does not affect my daily activity.
- Swelling affects my activity slightly.
- Swelling affects my activity moderately.
- Swelling affects my activity severely.
- Swelling in my knee prevents me from performing all daily activities.

5. To what degree does slipping of your knee affect your daily activity level?
- I never have slipping of my knee.
- I have slipping of my knee, but it does not affect my daily activity.
- Slipping affects my activity slightly.
- Slipping affects my activity moderately.
- Slipping affects my activity severely.
- Slipping of my knee prevents me from performing all daily activities.
6. To what degree does buckling of your knee affect your daily activity level?

☐ I never have buckling of my knee.
☐ I have buckling of my knee, but it does not affect my daily activity level.
☐ Buckling affects my activity slightly.
☐ Buckling affects my activity moderately.
☐ Buckling affects my activity severely.
☐ Buckling of my knee prevents me from performing all daily activities.

7. To what degree does weakness or lack of strength of your leg affect your daily activity level?

☐ My leg never feels weak.
☐ My leg feels weak, but it does not affect my daily activity.
☐ Weakness affects my activity slightly.
☐ Weakness affects my activity moderately.
☐ Weakness affects my activity severely.
☐ Weakness of my leg prevents me from performing all daily activities.

Functional Disability with Activities of Daily Living

8. How does your knee affect your ability to walk?

☐ My knee does not affect my ability to walk.
☐ I have pain in my knee when walking, but it does not affect my ability to walk.
☐ My knee prevents me from walking more than 1 mile.
☐ My knee prevents me from walking more than 1/2 mile.
☐ My knee prevents me from walking more than 1 block.
☐ My knee prevents me from walking.
9. Because of your knee, do you walk with crutches or a cane?
☐ I can walk without crutches or a cane.
☐ My knee causes me to walk with 1 crutch or a cane.
☐ My knee causes me to walk with 2 crutches.
☐ Because of my knee, I cannot walk even with crutches.

10. Does your knee cause you to limp when you walk?
☐ I can walk without a limp.
☐ Sometimes my knee causes me to walk with a limp.
☐ Because of my knee, I cannot walk without a limp.

11. How does your knee affect your ability to go up stairs?
☐ My knee does not affect my ability to go up stairs.
☐ I have pain in my knee when going up stairs, but it does not limit my ability to go up stairs.
☐ I am able to go up stairs normally, but I need to rely on use of a railing.
☐ I am able to go up stairs one step at a time with use of a railing.
☐ I have to use crutches or a cane to go up stairs.
☐ I cannot go up stairs.

12. How does your knee affect your ability to go down stairs?
☐ My knee does not affect my ability to go down stairs.
☐ I have pain in my knee when going down stairs, but it does not limit my ability to go down stairs.
☐ I am able to go down stairs normally, but I need to rely on use of a railing.
☐ I am able to go down stairs one step at a time with use of a railing.
☐ I have to use crutches or a cane to go down stairs.
☐ I cannot go down stairs.
13. How does your knee affect your ability to stand?
☐ My knee does not affect my ability to stand. I can stand for unlimited amounts of time.
☐ I have pain in my knee when standing, but it does not limit my ability to stand.
☐ Because of my knee I cannot stand for more than 1 hour.
☐ Because of my knee I cannot stand for more than 1/2 hour.
☐ Because of my knee I cannot stand for more than 10 minutes.
☐ I cannot stand because of my knee.

14. How does your knee affect your ability to kneel on the front of your knee?
☐ My knee does not affect my ability to kneel on the front of my knee. I can kneel for unlimited amounts of time.
☐ I have pain when kneeling on the front of my knee, but it does not limit my ability to kneel.
☐ I cannot kneel on the front of my knee for more than 1 hour.
☐ I cannot kneel on the front of my knee for more than 1/2 hour.
☐ I cannot kneel on the front of my knee for more than 10 minutes.
☐ I cannot kneel on the front of my knee.

15. How does your knee affect your ability to squat?
☐ My knee does not affect my ability to squat. I can squat all the way down.
☐ I have pain when squatting, but I can still squat all the way down.
☐ I cannot squat more than 3/4 of the way down.
☐ I cannot squat more than 1/2 of the way down.
☐ I cannot squat more than 1/4 of the way down.
☐ I cannot squat at all.
16. How does your knee affect your ability to sit with your knee bent?

- My knee does not affect my ability to sit with my knee bent. I can sit for unlimited amounts of time.
- I have pain when sitting with my knee bent, but it does not limit my ability to sit.
- I cannot sit with my knee bent for more than 1 hour.
- I cannot sit with my knee bent for more than 1/2 hour.
- I cannot sit with my knee bent for more than 10 minutes.
- I cannot sit with my knee bent.

17. How does your knee affect your ability to rise from a chair?

- My knee does not affect my ability to rise from a chair.
- I have pain when rising from the seated position, but it does not affect my ability to rise from the seated position.
- Because of my knee I can only rise from a chair if I use my hands and arms to assist.
- Because of my knee I cannot rise from a chair.
Appendix 9

Cincinnati Knee Rating Scale

### Sports Activity Scale

#### Level I (participates 4-7 days/week)
- Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
- Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling)
- No running, twisting, jumping (cycling, swimming)

#### Level II (participates 1-3 days/week)
- Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
- Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling)
- No running, twisting, jumping (cycling, swimming)

#### Level III (participates 1-3 times/month)
- Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
- Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling)
- No running, twisting, jumping (cycling, swimming)

#### Level IV (no sports)
- I perform activities of daily living without problems
- I have moderate problems with activities of daily living
- I have severe problems with activities of daily living: on crutches, full disability

### Change in Sports Activities

#### Decreased
- No change in sports activities
- No moderate / significant problems
- No problems

#### Stopped
- Given up sports activities
- Have moderate / significant problems
- Have problems

### Function ADL

#### Level ______

1. Walking
- Check box: normal, unlimited
- Check box: some limitations
- Check box: only 3-4 blocks possible
- Check box: less than 1 block, cane, crutch

2. Stairs
- Check box: normal, unlimited
- Check box: some limitations
- Check box: only 11-30 steps possible
- Check box: only 1-10 steps possible

3. Squatting / kneeling
- Check box: normal, unlimited
- Check box: some limitations
- Check box: only 6-10 possible
- Check box: only 0-5 possible

### Function Sports

#### Level ______

1. Straight running
- Check box: fully competitive
- Check box: some limitations, guarding
- Check box: definite limitations, half speed
- Check box: not able to do

2. Jumping / landing on affected leg
- Check box: fully competitive
- Check box: some limitations, guarding
- Check box: definite limitations, half speed
- Check box: not able to do

3. Hard twists / cuts / pivots
- Check box: fully competitive
- Check box: some limitations, guarding
- Check box: definite limitations, half speed
- Check box: not able to do

### Problems with Sports

#### Strain on your knee after participating for one hour without guarding or limitations in each of the three sports categories below:

<table>
<thead>
<tr>
<th>Sports</th>
<th>Problem Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strenuous Sport</td>
<td>Moderate problems during or after game</td>
</tr>
<tr>
<td>Moderate Sport</td>
<td>Severe problems; cannot participate</td>
</tr>
<tr>
<td>Light Sport</td>
<td>Moderate problems during or after game</td>
</tr>
</tbody>
</table>

### Total Points

<table>
<thead>
<tr>
<th>Sports Activity and Function Form</th>
<th>CINCINNATI KNEE RATING SYSTEM (FO7A)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

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**Patient Name**

**Date of Visit**

**Involved Knee**

**Date of Original Injury**

---

**DIRECTIONS:**

Using the KEY (at right), check the appropriate boxes on the four scales below which indicate the highest level you can reach WITHOUT having symptoms.

---

**KEY:**

<table>
<thead>
<tr>
<th>Scale</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Normal knee, able to do strenuous work/sports with jumping, hard pivoting</td>
</tr>
<tr>
<td>8</td>
<td>Able to do moderate work/sports with running, turning and twisting: symptoms with strenuous work/sports</td>
</tr>
<tr>
<td>6</td>
<td>Able to do light work/sports with no running, twisting or jumping: symptoms with moderate work/sports</td>
</tr>
<tr>
<td>4</td>
<td>Able to do activities of daily living alone; symptoms with light work/sports</td>
</tr>
<tr>
<td>2</td>
<td>Moderate symptoms (frequent, limiting) with activities of daily living</td>
</tr>
<tr>
<td>0</td>
<td>Severe symptoms (constant, not relieved) with activities of daily living</td>
</tr>
</tbody>
</table>

---

1. **PAIN**

   **Location of Pain:**
   - [ ] inner side
   - [ ] outer side
   - [ ] front/kneecap
   - [ ] back of knee
   - [ ] all over

   **Type of Pain:**
   - [ ] sharp
   - [ ] aching
   - [ ] throbbing
   - [ ] burning

   **Pain occurs on:**
   - [ ] sitting
   - [ ] standing
   - [ ] stairs
   - [ ] squatting
   - [ ] running/jumping

   **Pain relieved by:**
   - [ ] not doing sports
   - [ ] limiting daily activities
   - [ ] rest
   - [ ] pain not relieved

   **Kneecap grinding?**
   - [ ] yes
   - [ ] no

   **Knee stiffness?**
   - [ ] yes
   - [ ] no

---

2. **SWELLING**

   **Grade:**
   - [ ] out
   - [ ] in
   - [ ] slight
   - [ ] moderate
   - [ ] severe

---

3. **PARTIAL GIVING-WAY**

   **Grade:**
   - [ ] 1
   - [ ] 2
   - [ ] 3
   - [ ] 4
   - [ ] 5
   - [ ] 6
   - [ ] 7
   - [ ] 8
   - [ ] 9
   - [ ] 10

---

4. **FULL GIVING-WAY**

   **Grade:**
   - [ ] out
   - [ ] in
   - [ ] slight
   - [ ] moderate
   - [ ] severe

---

**Pain**

- [ ] by not doing sports
- [ ] by limiting daily activities
- [ ] by rest
- [ ] pain not relieved

---

**Catching/ Locking**

1. **Location:**
   - [ ] yes
   - [ ] no
   - My knee catches - it does not move for a few seconds but works out.

2. **Activity:**
   - [ ] yes
   - [ ] no
   - My knee locks - it does not move for five or more minutes at a time.

---

**Work Activity**

- [ ] full time
- [ ] part time
- [ ] full duty
- [ ] light duty
- [ ] not working

---

**Exercise Program**

- [ ] no limitations
- [ ] limitations
- [ ] moderate limitations
- [ ] severe limitations

---

**Follow-up Progress**

- [ ] making good progress
- [ ] slow progress, but better
- [ ] some problems with exercise
- [ ] exercise causes pain, problems
- [ ] doesn't apply

---

**Patient Grade**

Rate the overall condition of your knee at the present time. Circle one number below.

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5
- [ ] 6
- [ ] 7
- [ ] 8
- [ ] 9
- [ ] 10

---

**Average**

- Pain (x2)
- Swelling
- Partial giving-way
- Full giving-way

---

**Subtotal**

---

**SYMPTOM RATING FORM**

**CINCINNATI KNEE RATING SYSTEM 1999**

---

(Barber-Westin & Noyes 1999)
Appendix 10
Global Rating of Knee Function

How would you rate the current overall function of your knee during your usual daily activities on a scale from 0 to 100, with 100 being the level of your knee prior to your injury and 0 being the inability to perform any of your daily activities?

0 __________ 50% __________ 100%

1. Do you experience pain while running uphill? Yes □ No □ Unsure □
2. Do you experience pain while running downhill? Yes □ No □ Unsure □
3. Do you experience any symptoms when you stop suddenly while running? Yes □ No □ Unsure □
4. Do you experience any stiffness in your knee first thing in the morning? Yes □ No □ Unsure □
5. Does your knee stop you from doing any activities even if you don’t experience any symptoms? Yes □ No □ Unsure □
6. How many episodes of giving way have you had since your surgery? ______ per week/month/year
7. Did you have the following symptoms after your injury, before your surgery:
   • Pain Regularly □ Sometimes □ Never □
   • Swelling Regularly □ Sometimes □ Never □
   • Giving way Regularly □ Sometimes □ Never □
8. Do you feel your knee is still Improving □ Deteriorating □ Staying the same □
9. Are there any activities that you would hesitate to do because of your knee? Yes □ No □ Unsure □; if yes, what...............................................

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Appendix 11

DATA SHEET

6-meter hop for time

1. R: _____  L: _____
2. R: _____  L: _____
3. R: _____  L: _____

Cross-over hop for distance

1. R: _____  L: _____
2. R: _____  L: _____
3. R: _____  L: _____

Triple hop for distance

1. R: _____  L: _____
2. R: _____  L: _____
3. R: _____  L: _____

Single hop for distance

1. R: _____  L: _____
2. R: _____  L: _____
3. R: _____  L: _____

ANY ADDITIONAL INFORMATION DURING TESTING:
Neuromuscular control and physical performance following anterior cruciate ligament reconstruction using a semitendinosus/gracilis double-strand graft: are there different levels of coping?

A dissertation prepared by Elsje de Villiers (DVLELS001) in partial fulfilment of the requirements for the Master of Philosophy degree in Sports Physiotherapy (MPhil Sports Physiotherapy) from the University of Cape Town

(February 2006)
Declaration

I, Elsje Amerentia Maria de Villiers, hereby declare that the work on which this dissertation is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university.

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..............................................
(Signature)

..............................................
(Date)
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# List of abbreviations

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<th>Abbreviation</th>
<th>Full Form</th>
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<tr>
<td>ACL</td>
<td>Anterior Cruciate Ligament</td>
</tr>
<tr>
<td>ACLD</td>
<td>Anterior Cruciate Ligament Deficient</td>
</tr>
<tr>
<td>ACLR</td>
<td>Anterior Cruciate Ligament Reconstructed (individuals/group)</td>
</tr>
<tr>
<td>ADL</td>
<td>Activities of Daily Living</td>
</tr>
<tr>
<td>ASIS</td>
<td>Anterior Superior Iliac Spine</td>
</tr>
<tr>
<td>BF</td>
<td>Biceps Femoris</td>
</tr>
<tr>
<td>BPTB</td>
<td>Bone-patellar tendon-bone (graft)</td>
</tr>
<tr>
<td>CKRS</td>
<td>Cincinnati Knee Rating System</td>
</tr>
<tr>
<td>CKRS - SAF</td>
<td>Cincinnati Knee Rating Scale – Sports Activity and Function</td>
</tr>
<tr>
<td>EMG</td>
<td>Electromyography</td>
</tr>
<tr>
<td>GRA</td>
<td>Gracilis (muscle)</td>
</tr>
<tr>
<td>IKDC</td>
<td>International Knee Documentation Committee</td>
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<tr>
<td>KOS</td>
<td>Knee Outcome Survey</td>
</tr>
<tr>
<td>KOS - ADLS</td>
<td>Knee Outcome Survey - Activities of Daily Living Scale</td>
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<tr>
<td>LG</td>
<td>Lateral Gastrocnemius</td>
</tr>
<tr>
<td>LTV</td>
<td>Lean Thigh Volume</td>
</tr>
<tr>
<td>MG</td>
<td>Medial Gastrocnemius</td>
</tr>
<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>MVC</td>
<td>Maximum Voluntary Contraction</td>
</tr>
<tr>
<td>MVIC</td>
<td>Maximum Voluntary Isometric Contraction</td>
</tr>
<tr>
<td>PT</td>
<td>Patellar Tendon</td>
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<tr>
<td>RCT</td>
<td>Randomised Controlled Trial</td>
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<tr>
<td>RF</td>
<td>Rectus Femoris</td>
</tr>
<tr>
<td>ROM</td>
<td>Range of Motion</td>
</tr>
<tr>
<td>SG</td>
<td>Semitendinosus/gracilis (graft)</td>
</tr>
<tr>
<td>ST</td>
<td>Semitendinosus (muscle)</td>
</tr>
<tr>
<td>TA</td>
<td>Achilles Tendon</td>
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<tr>
<td>VL</td>
<td>Vastus Lateralis (muscle)</td>
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<tr>
<td>VM</td>
<td>Vastus Medialis (muscle)</td>
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Abstract

Background

The anterior cruciate ligament (ACL) is one of the primary stabilising ligaments of the knee joint and prevents anterior translation of the tibia in relation to the femur. There are three types of mechanoreceptors within the ACL which provide information about proprioception to the central nervous system, and play a role in dynamic joint stability. The ligament is commonly injured during sporting activities that involve jumping, twisting and turning. An ACL injury leads to a decrease in strength, proprioception and an alteration in movement patterns in the lower limbs.

ACL-reconstruction is indicated in cases where individuals have recurrent problems with episodes of giving way, pain and swelling. The two most popular autograft used in ACL-reconstruction are the bone-patellar tendon-bone graft and the semitendinosus/gracilis graft.

Recent studies proposed that two distinct groups of responders can be identified following ACL injury. ‘Copers’ were able to return to a relatively high level of function after their injury without episodes of giving way or instability of the knee joint. Individuals who were unable to return to their pre-injury level of sport participation or activity due to repeated episodes of giving way of their knee joint after ACL injury were classified as ‘non-copers’. Failure to recognise the differences between copers and non-copers, and how they respond following injury, could account for the inconsistencies in outcome measures described in the literature in the past, where most studies tended to
group all subjects with ACL injury together when studying different outcome measures. The underlying neuromuscular mechanisms for these differences in functional outcome following ACL-injury have not yet been identified. Furthermore, it has not been established whether individuals can also be classified as copers or non-copers following ACL-reconstruction and if these inherent differences in functional ability after ACL injury affect the outcome measures following surgery.

**Objective**

The objectives of this study were to (i) compare ACL-reconstructed individuals to a normal, healthy control group to assess whether there are any differences in self-reported function, muscle strength or functional outcome measures, and (ii) separate individuals who had undergone ACL reconstruction into specific 'coper' or 'non-coper' groups according to self-reported function. These identified groups were then correlated with outcome measures, particularly the neuromuscular performance during different strength and functional tests, to identify any potential neuromuscular mechanism responsible for the difference in functional outcome following ACL-reconstruction.

**Methods**

Seventeen subjects, who had undergone previous ACL-reconstruction using a double-strand semitendinosus/gracilis autograft, were studied at a minimum of 24 months following surgery. Nine males and eight females (mean age 29.9 ± 9.5 years) participated in this study. Isometric and isokinetic strength (concentric at 60° and 180°/s, and eccentric at 60°/s) of the quadriceps and hamstring muscles were tested in both injured
and non-injured limbs using a Biodex dynamometer. Each subject then performed a step up/down test, and four hop tests, bilaterally, during a single testing session. Electromyographic data was collected with surface electrodes from four muscles (vastus medialis, vastus lateralis, semitendinosus and biceps femoris) during the isokinetic strength testing and the functional step up/down test. EMG data was normalised to the mean amplitude of three maximum voluntary contractions measured during isometric strength testing.

Each subject completed three subjective questionnaires regarding their present symptoms and sporting activities; the Knee Outcome Survey - Activities of Daily Living Scale (KOS-ADLS), a Global Rating Score (GRS) and the Cincinnati Knee Rating Scale - Sports Activities Scale (CKRS - CSAS).

Ten age and gender matched controls (mean age 30 ± 7.3 years) were recruited as there is evidence to suggest that an ACL-injury can lead to bilateral adaptations. Group differences between the ACL-reconstructed and control groups were determined using independent t-tests.

In the second part of the study the subjects who had undergone ACL-reconstruction were classified as copers or non-copers according to four criteria based on timed hop test score, two self-reported knee function scores and number of episodes of giving way. These two groups were then compared for strength, functional hop tests and EMG data. Group differences were determined using independent t-tests.
Results

The control group scored significantly higher for the self-reported measures of function (KOS-ADLS and CKRS-SAS) compared to the ACL-reconstruction group. However, there were no significant differences for isokinetic quadriceps and hamstring muscle strength, functional hop tests and EMG measures of muscle activity in the VMO, VL, ST and BF muscles between the ACL-reconstructed and control groups. The time to reach peak torque for the hamstring muscle of the involved limb during the concentric strength testing at 180°/s was significantly faster in the ACL-reconstructed group compared to the control group. The time needed to reach peak torque of the hamstring muscle of the involved limb during eccentric testing at 60°/s was significantly slower in the ACL-reconstructed group compared to the control group.

In the second part of the study seven ACL-reconstructed subjects were classified as copers while ten ACL-reconstructed subjects were classified as non-copers. The copers scored significantly higher in the self-reported measures of knee function, the KOS-ADLS and GRS. However, there were no significant differences for isokinetic quadriceps and hamstring muscle strength, functional hop tests and EMG measures of muscle activity in the VMO, VL, ST and BF muscles between the involved and uninvolved limb of the coper and non-coper groups.

Conclusion

There were no differences in strength, functional hop tests or EMG activity between the ACL-reconstructed group and control group. This suggests that for these neuromuscular
outcome measures, ACL-reconstruction using a double-strand semitendinosis/gracilis graft delivers satisfactory outcome comparable to that of normal age and sport-matched individuals. The significant difference in time to reach peak torque for the hamstring muscle between the limbs of the ACL-reconstructed and control groups that was found in the present study may be a 'protective' mechanism or at least an alteration caused by the injury.

Copers and non-copers demonstrated no significant differences in strength, functional ability and EMG activity. This suggests that the differences in self-reported measures of knee function between the two groups can not be explained by the neuromuscular and physical outcome measures assessed in the present study. It is possible that the dissociation between self-reported functional capacity and physical performance between the coper and non-coper groups could be explained by the psychological profile of these individuals.

**Key words**

ACL-reconstruction; neuromuscular performance; muscle strength; hamstring graft