AN EVALUATION OF PATIENTS WITH ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION WITH AN ACCELEROMETER AND THE STEP-UP-AND-OVER TEST

By

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Abstract

Evaluating patient knee function after anterior cruciate ligament reconstruction (ACLR) can be difficult. With current evaluation methods, some patients are unable to return to their previous level of physical activity and if they do, they have a high risk of re-injury. One reason for these poor outcomes could be a lack of evaluation options in the clinic. Clinical evaluations require inexpensive and objective tests that have low physical demand. One objective and low demand test is the step-up-and-over (SUAO). Presently, the test uses a force plate, an expensive device. Replacing the force plate with an accelerometer could make the SUAO test an inexpensive evaluation tool of ACLR patients. Therefore, this thesis had three objectives. First, to discover if an accelerometer is a valid alternative to a force plate for the SUAO test. Second, to determine if the accelerometer-modified SUAO test is performed differently by ACL-intact individual and ACLR patients. Third and final, to determine if a relationship exists between SUAO test performance and subjective knee function.

Two studies were completed for this thesis. In the first study, 17 ACL-intact individuals completed the SUAO test while being measured with a force plate and an accelerometer. In the second study, 26 ACL-intact individuals and 25 ACLR patients completed questionnaires on subjective knee function and fear of re-injury, then were measured with an accelerometer during the SUAO test.

Results showed that the force plate and accelerometer measures were strongly correlated. Results also showed that the SUAO test, was performed differently by ACL-intact individuals and ACLR patients, and that the test performance was correlated to subjective knee function. Together, these results demonstrate that the SUAO test, with an accelerometer, is a clinically
viable option on which normal and abnormal knees perform differently, and that the performance is related to the person’s opinion of their knee’s function.
Co-Authorship

Co-authorship of this thesis’ manuscripts belong to Dr. Patrick Costigan (Chapters 4 and 5) and Dr. Davide Bardana (Chapter 5).
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Chapter 1

General Introduction

Anterior cruciate ligament (ACL) tears are among the most common, costly, and difficult sport injuries to rehabilitate. For every 1000 sport exposures, injury rates range from 0.17 for collegiate basketball and 0.21 for collegiate soccer, to 0.33 in elite handball and 0.49 in alpine skiing (Prodromos, Han, Rogowski, Joyce, & Shi, 2007). Injured athletes who want to restore their original knee function and return to sport often require surgical reconstruction of their torn ACL. As a result, approximately $4 billion is spent annually in the United States to perform 200,000 ACL reconstruction (ACLR) surgeries (Brophy, Wright, & Matava, 2009). However, surgery and rehabilitation may not fully restore normal lower limb kinematics, kinetics and leg strength, which may not allow the patient to return to their normal activities and, in the worst case, increase the risk of re-injuring the ACL (Decker, Torry, Noonan, Riviere, & Sterett, 2002; DeVita, Hortobagy, & Barrier, 1998; Ernst, Saliba, Diduch, Hurwitz, & Ball, 2000; Hewett et al., 2005; L A Hiemstra, Webber, MacDonald, & Kriellaars, 2000; Laurie A Hiemstra, Webber, MacDonald, & Kriellaars, 2004, 2007; Mattacola et al., 2002; Paterno et al., 2010; Paterno, Ford, Myer, Heyl, & Hewett, 2007; Salem, Salinas, & Harding, 2003; Tashman, Collon, Anderson, Kolowich, & Anderst, 2004).

From injury through to surgery and rehabilitation knee function is evaluated. Though the tests used vary by clinic, there are four evaluations that are used widely: 1) the International Knee Documentation Committee Subjective Knee Form (IKDC-SKF), 2) the laxity test, 3) the strength test, and 4) the hop tests (Myer, Paterno, Ford, Quatman, & Hewett, 2006; Shelbourne & Nitz, 1990; van Grinsven, van Cingel, Holla, & van Loon, 2010; Werstine, 2009). The IKDC-SKF is a patient-completed questionnaire that evaluates their knee symptoms, function, and
ability to perform in sport (Irrgang et al., 2001). The laxity test, using the KT-1000 Knee Arthrometer, evaluates ACL ligament laxity (Harter et al., 1988). The strength test is comprised of two components. First, the symmetry of the involved and uninvolved leg’s knee strength is evaluated and second, the symmetry of the involved and uninvolved leg's knee extensor to knee flexor strength ratio is evaluated (Myer et al., 2006; van Grinsven et al., 2010). The hop tests differ from the strength tests, as the three hop tests, the single leg hop, vertical hop, and the side hop, evaluate maximal knee power and endurance (Gustavsson et al., 2006; van Grinsven et al., 2010) rather than maximal strength. These tests, used singularly or in concert, evaluate a patient’s knee function and passing these tests indicates a return to normal function.

Even if patients pass the tests, patients have a fear of re-injury. This fear of re-injury is justified. In cohorts followed after ACLR, up to 23% of patients suffered an injury to their ACL graft or their contralateral ACL (Paterno et al., 2010; Pinczewski et al., 2007; Salmon, Russell, Musgrove, Pinczewski, & Refshauge, 2005; Wright et al., 2007). The fear of re-injury is prominent early in rehabilitation and can even persist once rehabilitation is complete (Ardern, Webster, Taylor, & Feller, 2011; Chmielewski et al., 2008; Kvist, Ek, Sporstedt, & Good, 2005). One reason for this could be from maximal effort knee testing. Maximal effort evaluations like the hop tests assess maximal knee power and endurance (Augustsson, Thomeé, & Karlsson, 2004; Gustavsson et al., 2006; Juris et al., 1997; Paterno et al., 2007; Thomeé et al., 2012), putting patients in a situation where they may stress their knee similarly to their initial injury, which may promote their general fear of re-injury. Additionally, many individuals with ACLR have not regained normal knee flexor and extensor strength after rehabilitation (L A Hiemstra et al., 2000; Laurie A Hiemstra et al., 2007), which means that without normal knee strength, assessing knee power and endurance with the hop tests may lead to an inaccurate representation of knee function due to the patient’s fear of re-injury.
Furthermore, evaluations that require a maximal, powerful effort cannot be performed throughout the rehabilitation process. Powerful movements, such as plyometric exercises, are contraindicated to the recovery of the ACL reconstructed knee early in rehabilitation, since the strength of the graft is not optimal (Cascio, Culp, & Cosgarea, 2004; Lahav & Burks, 2005). In many cases, evaluations, such as the hop tests, are completed at 3-6 months after ACLR (Shaw, Chipchase, & Williams, 2004; van Grinsven et al., 2010) and only after a clinician has cleared the patient for such movements. Before this stage, strenuous objective tests are normally not used, meaning a patient’s knee function throughout rehabilitation is not known fully. This situation may be ameliorated with an objective test that can be completed with less physical demand.

An alternative low demand, objective test, that may not be feared and can be used throughout ACLR rehabilitation, is the step-up-and-over (SUAO) test. To execute the step-up-and-over test, the patient stands behind a 305mm high box that sits on a force plate. Then, as quickly as they can, they step up onto the box with their lead leg, carry their body over the box, and land with their trail leg contacting the force plate on the opposite side of the box, completing the test (Chmielewski, Wilk, & Snyder-Mackler, 2002; Lin, Hsu, Chang, Chiou, & Lu, 2010; Mattacola, Jacobs, Rund, & Johnson, 2004) (Figure 1.1). The trail leg, though the last to leave, is the first to impact on the opposite side of the box. After the test is completed, three variables that evaluate knee function are extracted from the force plate data: the Lift Index, Impact Index and Movement Time. The Lift Index is the maximal vertical force recorded as the body is raised up onto the box divided by the participant’s body mass and characterizes the concentric control of the lead leg’s knee extensors. The Impact Index is the maximal vertical force recorded at the touch-down of the trail leg divided by the participant’s body mass and characterizes the eccentric control of the lead leg’s knee extensors. Movement Time is the time from the initiation of
movement until touch-down of the trail leg and includes both the concentric and eccentric phases of the knee’s extensors. These measures indicate the knee function of individuals with ACLR (Chmielewski et al., 2002; Lin et al., 2010; Mattacola et al., 2004), and, unlike the hop tests, are not acquired from maximal jumping, landing or performance to fatigue.

Figure 1.1. The SUAO test. Shown are the start (left), lift (center) and impact (right) phases of the test.

While measures from the SUAO test can be acquired with sub-maximal effort, the measuring device, a force plate, is typically not available to clinicians. To make the SUAO test more available, an economical and simple alternative to the force plate is needed. Two of the variables, Lift Index and Impact Index, are force values divided by a mass which gives us acceleration and, as for Movement Time, any motion requires an acceleration. Therefore, rather than a force plate, we should be able to use an accelerometer. However, it is unknown if the accelerometer is a valid alternative to the force plate for the SUAO test. If so, it is also unknown if the modified SUAO test, using the accelerometer, is performed differently by ACL-intact
individuals and ACLR patients, and if performance on the SUAO test is related to individual-reported knee function.
Chapter 2

Review of Related Literature

2.1 ACL Injury, Treatment, and Rehabilitation

2.1.1 Mechanisms of ACL Injury

The mechanisms of ACL injury can be divided into injuries resulting from an object (inanimate, or another person) making direct contact to the knee, called contact mechanisms, and those that result without this contact, called non-contact mechanisms. The non-contact mechanism is more prevalent, causing 70% of all ACL injuries (Boden, Dean, Feagin, & Garrett, 2000; McNair, Marshall, & Matheson, 1990). The mechanism is characterized by a sudden deceleration, with the knee at 30° of flexion or less, often when landing from a jump or pivoting to change direction (Boden et al., 2000; McNair et al., 1990) (Figures 2.1 and 2.2). Thus, for the non-contact mechanism of ACL injury, the tibia translates forward and rotates externally with the knee in valgus (Ford, Myer, & Hewett, 2003; Hewett et al., 2005; Levine et al., 2013; Markolf et al., 1995; Olsen, Myklebust, Engebretsen, & Bahr, 2004; Sakane et al., 1999; Shin, Chaudhari, & Andriacchi, 2009; Woo, Debski, Withrow, & Janaushek, 1999). The non-contact mechanism of ACL injury is common and well understood.
Figure 2.1. Mechanism of anterior cruciate injury resulting from a pivot. Adapted from Boden and colleagues (2000).
Figure 2.2. Mechanism of anterior cruciate ligament injury from landing from a jump. Adapted from Boden and colleagues (2000).

2.1.2 Biomechanical Risk Factors for ACL Injury

Also well understood are the non-contact ACL injury risk factors. Many factors have been identified and can be categorized as environmental, anatomical, hormonal, neuromuscular and biomechanical. For a comprehensive description of the non-biomechanical risk factors, see Alentorn-Geli and colleagues (2009).
Biomechanical risk factors are defined as risk factors associated with an individual’s movement and include dynamic knee valgus, internal hip rotation, and vertical ground reaction force.

1. *Dynamic knee valgus.* Dynamic knee valgus is a widely accepted ACL injury predictor. It is defined as the knee joint’s medial collapse with movement, often when landing and pivoting (Figure 2.3). Components of dynamic knee valgus, which are the knee abduction moment and angle, differ between ACL-intact and ACL-deficient knees, and are predictive of ACL injuries (Hewett et al., 2005; Paterno et al., 2010). In their cohort study, Hewett and colleagues (2005) found that knee abduction moment predicted which individuals injured their ACL with 73% specificity and 78% sensitivity. Subsequent injuries to the ACL can also be predicted by dynamic knee valgus, as demonstrated by Paterno and colleagues (2010). In their study, patients who had a greater frontal plane knee range of motion were more likely to have a subsequent ACL injury. Further support of the dynamic knee valgus risk factor can be drawn from in-vivo and cadaveric knee studies. In these studies, ACL strain increased with knee abduction (Chaudhari, Hearn, Leveille, Johnson, & Andriacchi, 2003; Shin et al., 2009). Finally, hip motion may contribute to dynamic knee valgus as increases in the hip adduction moment are reflected by increases in dynamic knee valgus (Ford et al., 2003; Hewett et al., 2005; Imwalle, Myer, Ford, & Hewett, 2009). Dynamic knee valgus, particularly evident when landing or pivoting, is a key biomechanical risk factor for ACL injury.
2. **Internal hip rotation.** An additional biomechanical risk factor for ACL injury is excess internal hip rotation. This excess motion has been observed during landing and pivoting to quickly change direction, two movements that, as mentioned, are associated with ACL injury (Imwalle et al., 2009; McLean, Huang, & van den Bogert, 2005; Paterno et al., 2010). That being said, internal hip rotation may not act alone. There is some evidence that internal hip rotation and dynamic knee valgus are related, but the evidence is not conclusive (Imwalle et al., 2009; McLean et al., 2005). It is believed that internal hip rotation may affect dynamic knee valgus since rotation of the hip likely strains ligaments that stabilize the knee in the frontal plane. Regardless of its relationship with knee abduction, internal hip rotation is an independent predictor of ACL injury (Paterno et al., 2010).
3. **Vertical ground reaction force.** In addition to dynamic knee valgus and internal hip rotation, vertical ground reaction force may be a risk factor for an ACL injury. This risk factor can be characterized in two ways: by its peak and by the rate of force development. The peak vertical ground reaction force at landing is larger for individuals who have experienced an ACL injury than those who did not (Hewett et al., 2005), but no prospective studies have explored the rate of force development. Also, the vertical ground reaction force from landing and pivoting can be influenced by sagittal plane motions of the hip, knee and ankle. Increases in hip, knee and ankle flexion can reduce the peak vertical ground reaction force and reduce the rate of force development (Paterno et al., 2010; Thomas, McLean, & Palmieri-Smith, 2010; Torry et al., 2004).

There is a consensus among the literature that excess dynamic knee valgus, internal hip rotation and vertical ground reaction force are biomechanical predictors of ACL injury. Unlike some risk factors, biomechanical risk factors can be mitigated with training (Chappell & Limpisvasti, 2008; Dempsey, Lloyd, Elliott, Steele, & Munro, 2009; Lim et al., 2009; McCurdy, Walker, Saxe, & Woods, 2012; Pollard, Sigward, Ota, Langford, & Powers, 2006; Zebis et al., 2008), making them an appealing focus of ACL injury treatments.

**2.1.3 ACL Injury Treatment Options**

Typically individuals who have injured their ACL have two treatment options: conservative or surgical. When treated conservatively, patients do not receive surgery and may return to their physical activities more quickly than those who undergo surgical treatment. With surgical treatment, a tissue graft is created in the knee to mimic the function of the ACL. Because this treatment requires a lengthy rehabilitation process, patients are unable to fully
participate in their physical activities for approximately six months after the surgery (Shelbourne & Nitz, 1990). Patients and clinicians, together, must decide on the treatment option.

When selecting the treatment, clinicians consider the patient’s activities and their age. Patients who regularly run, jump and pivot in their physical activities usually receive surgery in order to stabilize the knee (Daniel et al., 1994). Without the ACL graft, as in conservative treatment, knee hypermobility may contribute to future lower limb injuries (Myer, Ford, Paterno, Nick, & Hewett, 2008). An additional activity consideration is the patient’s competitive level. Patients who are competitive athletes return to their pre-injury activity level more often if they receive surgery than if they receive conservative treatment (Fithian, 2005). These competitive patients typically complete long, frequent and/or intense physical tasks that may contribute to knee loading and future injury risk, though these have not yet been fully studied. Another influence on the treatment decision is the patient’s age. Older patients receive surgical treatment less often than younger patients (Daniel et al., 1994). However, younger patients may also be more active than older patients, suggesting that the patient’s activity type and level are key to the treatment decision, not their age (Brandsson, Kartus, Larsson, Eriksson, & Karlsson, 2000; Seng, Appleby, & Lubowitz, 2008).

Regardless of the patient’s activities and age, some clinicians encourage surgical treatment. Although surgical treatment can result in patients reducing their physical activity level for several months before and after their operation, the treatment reduces knee laxity and subsequent meniscal surgeries to repair torn menisci, and improves the patient’s subjective knee function, all more than patients who are treated conservatively (Clancy, Ray, & Zoltan, 1988; Fithian, 2005; Kessler et al., 2008). For many patients and clinicians, the long-term reduction in knee laxity, future meniscal surgery, and increase in knee function with surgical treatment outweigh the short-term reduction in physical activity level.
2.1.4 ACL Reconstruction Rehabilitation

In the surgical treatment of the ACL injury, clinicians attempt to restore normal knee function to patients by performing ACL reconstruction (ACLR). In this surgery, the ACL ligament is repaired using a hamstrings graft, from the semitendinosus and gracilis tendons, or a patellar tendon graft. Afterwards, in rehabilitation, the challenge is for patients to reach normal knee function. The concept of “knee function” is difficult to operationalize, but one method to do so is in relation to physical activity, where normal knee function is the ability for a patient to complete their daily physical activities (ie. daily living, work, sports) unhindered. Since physical activity is hindered after surgery, studying and improving a patient’s deficits in rehabilitation is important to regain normal knee function.

Knee function can be regained by addressing the following post-surgical deficits (Myer et al., 2006; Shelbourne & Nitz, 1990; van Grinsven et al., 2010; Werstine, 2009):

1. **Range of motion.** Following ACLR, the involved knee's range of motion is very limited, so it is addressed immediately with mobilizations and stretching. For most individuals, stretching the knee flexors and extensors with a 30 second hold improves knee range of motion (Shrier & Gossal, 2000). Achieving full, pain-free range of motion is essential to properly progress patients to knee strengthening exercises that require the full range of motion of motion.

2. **Gait.** It is well known that joint loading of both the involved and uninvolved limbs changes after ACL injury (Decker et al., 2002; DeVita et al., 1998; Ernst et al., 2000; Mattacola et al., 2002; Paterno et al., 2007; Salem et al., 2003; Tashman et al., 2004; von Porat et al., 2006). These compensations increase the risk of suffering a subsequent ACL injury to either limb (Paterno et al., 2010; Pinczewski et al., 2007; Salmon et al., 2005; Wright et al., 2007), so clinicians emphasize early weight bearing after ACLR in an attempt to mitigate gait changes (Shelbourne & Nitz, 1990).
3. **Proprioception.** Immediately after ACL injury, pre-operative patients have an altered neuromuscular response and proprioception (Barrack, Skinner, & Buckley, 1989; Wojtys & Huston, 1994). This can be trained during rehabilitation with balance exercises. When balance exercises are included in the rehabilitation program, the patient's knee function improves (Risberg, Holm, Myklebust, & Engebretsen, 2007).

4. **Cardiovascular fitness.** As a result of ACLR, patients are unable to maintain their pre-injury level of cardiovascular fitness. The intensity of cardiovascular exercises after ACLR increases as patients progress through rehabilitation stages (Shelbourne & Nitz, 1990; Werstine, 2009), with the goal of reaching pre-injury fitness levels before fully returning to physical activity.

5. **Muscular strength.** Since high knee loading is a factor predicting ACL injury (Hewett et al., 2005), it is important to decrease the loading by increasing knee extensor and flexor strength. Although improving muscular strength around the knee is a focus of rehabilitation, deficits in knee extensor and flexor strength have been demonstrated after a return to physical activity (L A Hiemstra et al., 2000; Laurie A Hiemstra et al., 2007; Mattacola et al., 2002; von Porat et al., 2006). Targeting the strength deficit specific to the graft-harvested muscle, especially knee extensor strength, is important before more demanding movements can be practiced.

Therefore, knee deficits exist in range of motion, gait, proprioception, cardiovascular fitness and muscular strength, all of which must be targeted during rehabilitation.

**2.1.5 Patient Outcome after ACL Reconstruction Rehabilitation**

Despite a strong understanding of the knee deficits that need to be targeted in rehabilitation, there are mixed views on the patient’s outcome afterwards. Fortunately, the surgical procedure is successful for many individuals. The procedure and subsequent rehabilitation corrects knee joint laxity, protects against meniscal loads and improves subjective
knee function (Fithian, 2005; Kessler et al., 2008; Papageorgiou et al., 2001). However, many patients do not return to their pre-injury activity level (Fithian, 2005; Kvist et al., 2005). Those who do are at a high risk of tearing their graft or other ACL (Paterno et al., 2010; Pinczewski et al., 2007; Salmon et al., 2005; Wright et al., 2007). More long-term, individuals who tear their ACL are at an increased risk of having an osteoarthritic knee (Lohmander, Englund, Dahl, & Roos, 2007; von Porat, Roos, & Roos, 2004). It is well known that osteoarthritis is a disease that limits an individual’s participation in recreational and competitive physical activities. Although the surgery stabilizes the knee, it may do so at a cost.

The mixed views regarding patient outcomes could be a result of releasing patients to physical activity too early. The current goal is to return patients to their physical activities when their time since surgery is six months (Shelbourne & Nitz, 1990). As an evaluator of knee function, time since surgery seems inappropriate given how many patients fail knee function tests after six months. For instance, one of the most common tests of knee function, the single-leg horizontal hop test, requires an involved leg performance that is at least 85% of the uninvolved leg to pass. With this criteria, fewer than half of patients pass after six months of rehabilitation (Thomeé et al., 2012). The use of rehabilitation duration as a return to physical activity criteria is particularly apparent in a review published by Barber-Westin and Noyes (2011). In their 2011 review, 32% of the 264 ACLR studies selected included only rehabilitation duration as a return-to-physical activity criteria. Worse, 40% of the studies did not include any criteria for a return-to-physical activity. To mitigate the number of patients that have a poor post-ACLR outcome, an alternative evaluation of knee function to rehabilitation time is required.
2.2 Evaluating Knee Function during ACL Reconstruction Rehabilitation

There are many different assessments of knee function that exist, requiring a decision about which assessments to use. These assessments include patient questionnaires, manual tests conducted by clinicians, and maximal and sub-maximal effort tests performed by patients. With so many assessment methods, it can be a challenge for clinicians to decide which test(s) are most appropriate. To make an evidence-based decision, clinicians must evaluate and compare each test’s advantages and disadvantages.

2.2.1 Patient Questionnaires

A variety of patient questionnaires have been developed by clinicians to better understand knee function (Briggs et al., 2009; Irrgang et al., 2001; Lundberg, Styf, & Carlsson, 2004; Marx, Stump, Jones, Wickiewicz, & Warren, 2001; Marx, Jones, et al., 2001; Mohtadi, 1998; Roos, Roos, Lohmander, Ekdahl, & Beynnon, 1998; Sullivan & Pivik, 1995; Woby, Roach, Urmston, & Watson, 2005). As a result, it is difficult to decide which ones are most appropriate. In an attempt to identify the most appropriate questionnaires, they have been classified by what they evaluate: 1) global knee function, 2) ACL-specific knee function or 3) a domain of knee function. For a summary of all questionnaires reviewed, see Table 2.1.
Table 2.1. Questionnaires reviewed, their classification, and the domain(s) of knee function they evaluate.

<table>
<thead>
<tr>
<th>Questionnaire</th>
<th>Classification</th>
<th>Domains Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>International Knee Documentation Committee Subjective Knee Form (IKDC-SKF) (Irrgang et al., 2001)</td>
<td>Global</td>
<td>Symptoms, sports activities</td>
</tr>
<tr>
<td>Knee Injury and Osteoarthritis Outcome Score (KOOS) (Roos et al., 1998)</td>
<td>Global</td>
<td>Symptoms, sports activities, daily living activities, pain, quality of life</td>
</tr>
<tr>
<td>Cincinnati Knee-Rating System (Marx, Jones, et al., 2001)</td>
<td>Global</td>
<td>Symptoms, pain, activity level</td>
</tr>
<tr>
<td>Lysholm Scale (Marx, Jones, et al., 2001)</td>
<td>Global</td>
<td>Symptoms, daily living activities, pain</td>
</tr>
<tr>
<td>Mohtadi ACL Quality of Life (ACL-QOL) (Mohtadi, 1998)</td>
<td>ACL-specific</td>
<td>Symptoms, sports activities, daily living activities, work activities, quality of life (lifestyle and social/emotional characteristics)</td>
</tr>
<tr>
<td>Tampa Scale for Kinesiophobia (TSK) (Lundberg et al., 2004)</td>
<td>Domain</td>
<td>Fear of re-injury</td>
</tr>
<tr>
<td>Shortened Tampa Scale for Kinesiophobia (TSK-11) (Woby et al., 2005)</td>
<td>Domain</td>
<td>Fear of re-injury</td>
</tr>
<tr>
<td>Pain Catastrophizing Scale (PCS) (Sullivan &amp; Pivik, 1995)</td>
<td>Domain</td>
<td>Fear of pain</td>
</tr>
<tr>
<td>Tegner Activity-Level Scale (Briggs et al., 2009)</td>
<td>Domain</td>
<td>Activity level</td>
</tr>
<tr>
<td>Marx Activity-Rating Scale (Marx, Stump, et al., 2001)</td>
<td>Domain</td>
<td>Activity level</td>
</tr>
</tbody>
</table>

Of the four global knee function questionnaires, the IKDC-SKF is the most effective. It is both a valid and reliable questionnaire (Irrgang et al., 2001). Unlike other questionnaires, patients completing the IKDC-SKF can be compared to normative scores (Anderson, 2005). These normative scores were developed for healthy men and women, and can be used to indicate
if a patient is ready to return to physical activity (Myer et al., 2006), a strength of the IKDC-SKF. The questionnaire does have a weakness, as it evaluates fewer domains of knee function than other global knee function questionnaires (Table 2.1). For instance, the KOOS measures daily living activities, pain and quality of life, while the IDKC-SKF does not. Each domain of knee function in the KOOS can be measured independently, which may provide a more detailed evaluation of knee function than the IKDC-SKF (Roos et al., 1998). The questionnaire’s strength outweighs its weakness. If a more detailed understanding of knee function is desired by the clinician and/or patient, additional domains of knee function can be measured using other questionnaires (Briggs et al., 2009; Lundberg et al., 2004; Marx, Stump, et al., 2001; Sullivan & Pivik, 1995; Woby et al., 2005). The IKDC-SKF is important to patients (Tanner, Dainty, Marx, & Kirkley, 2007) and provides a single overall score that can be compared to normative values, something not possible with other global knee function questionnaires.

An injury-specific questionnaire alternative to global knee function questionnaires, for ACL-deficient patients, is Mohtadi’s ACL-QOL (Mohtadi, 1998). Like the IKDC-SKF, the ACL-QOL is a valid and reliable assessment of knee function (Mohtadi, 1998). As an ACL-specific questionnaire, the ACL-QOL is considered more important to patients with ACL-deficiency than global knee function questionnaires (Tanner et al., 2007). Unfortunately, the ACL-QOL has not been validated for an ACLR patient group and there are no norms for the ACL-QOL. Though the ACL-QOL is more important than the IKDC-SKF to patients, patients still find the IKDC-SKF highly important and, with normative standards, so do clinicians.

Clinicians also need to understand specific constructs of knee function, including a patient’s fear of pain, fear of re-injury and activity level. These can be considered as knee function domains because they are or may be related to global knee function (Chmielewski et al., 2008; Kvist et al., 2005). These domains can be measured with questionnaires (Table 2.1) and,
more importantly, they provide further insight into a patient’s ability to recover from ACLR. For example, Sullivan and colleagues (2002; 1998) have found that a fear of pain, more than pain alone, predicts an individual’s physical activity intolerance. Physical activity is a major component of ACLR rehabilitation, so a patient’s fear of pain will likely influence their recovery. Recovery can also be influenced by fear of re-injury. As with fear of pain, patients who are more fearful of re-injury are less likely to return to their pre-injury physical activity level (Kvist et al., 2005). A patient’s fear of pain and re-injury are two useful measures that explain their limited physical activity level. An evaluation of activity level is also needed to see if patients have returned to their pre-injury activity level, an important factor for the ACLR to be considered a success. Further insight into a patient’s recovery is gained by measuring fear of pain, fear of re-injury and activity level.

While knee function questionnaires are important to patients and valuable for clinicians, the questionnaires are based entirely on the patient’s opinion. The patient’s opinion on its own does not provide a complete assessment of knee function. To supplement the patient’s opinion, the evaluation of knee function should also include the clinician’s assessment.

2.2.2 Manual Tests

One of the main ways a clinician assesses the ACL graft is with manual tests. Manual tests evaluate the knee joint’s laxity. The knee’s laxity increases after an ACL tear (Daniel, Stone, Sachs, & Malcom, 1985), so the ability of the graft to resist knee motion may be an important indicator of knee function. Though knee joint laxity can be assessed using the Lachman’s, anterior drawer and pivot shift tests (Katz & Fingeroth, 1986), a more objective method is to use the arthrometer test (Daniel et al., 1985).
The arthrometer test quantifies anterior tibial translation at the knee joint. At the joint, the patient is instrumented with a KT-1000 Arthrometer and the clinician can use the handle on the device to apply a force. An audible signal indicates when the clinician reaches the desired force on the handle, and a reading of the joint laxity is then given with an accuracy of $\pm 0.5$ mm (Daniel et al., 1985). The test is an effective diagnostic test for an ACL tear (Daniel et al., 1985).

Though the arthrometer test is useful for diagnosing ACL tears, its ability to evaluate knee function after ACLR is debatable. The patient’s subjective knee function does not appear to be related to their knee joint laxity (Harter et al., 1988; Kocher, Steadman, Briggs, Sterett, & Hawkins, 2004; Risberg, Holm, Tjomsland, Ljunggren, & Ekeland, 1999; Ross, Irrgang, Denegar, McCloy, & Unangst, 2002). According to Myer and colleagues (2008), knee joint laxity may predict ACL re-injury, though others disagree (Paterno et al., 2010; Uhorachak et al., 2003). Therefore, the arthrometer test may be able to identify patients that are at a high risk of suffering a second ACL injury, but cannot be used to evaluate knee function across ACLR rehabilitation.

### 2.2.3 Maximal Effort Tests

Another way clinicians can assess knee function after ACLR is with maximal effort tests. Maximal effort tests are used most often at the return-to-physical activity stage of ACLR rehabilitation (Myer et al., 2006; van Grinsven et al., 2010; Werstine, 2009). Many different tests have been created, including the isokinetic knee strength (Keays, Bullock-Saxton, & Keays, 2000; Lephart, Ferris, Riemann, Myers, & Fu, 2002; Mattacola et al., 2002; Wilk, Romaniello, Soscia, Arrigo, & Andrews, 1994), single-leg horizontal hop (Gustavsson et al., 2006), single-leg vertical hop (Gustavsson et al., 2006), side hop (Gustavsson et al., 2006), drop vertical jump (Ford et al., 2003) and agility (Myer et al., 2006; Pauole, Madole, Garhammer, Lacourse, &
Rozenek, 2000) tests. Of these tests, the most commonly used by clinicians are the isokinetic knee strength and single-leg horizontal hop tests (Myer et al., 2006; van Grinsven et al., 2010; Werstine, 2009).

The isokinetic knee strength test is a test of maximal extensor and flexor strength performed on an isokinetic dynamometer (Keays et al., 2000; Lephart et al., 2002; Wilk et al., 1994). On this machine, the patient’s leg is secured such that the only moving joint is the knee. After the angular velocity and range of motion of the movement are selected, the patient completes the specified number of knee extension/flexion cycles at maximal effort. Clinicians extract the symmetry of the involved and uninvolved leg's peak torque, and the symmetry of the involved and uninvolved leg's ratios of peak knee extensor to knee flexor torque to evaluate knee function (Myer et al., 2006; van Grinsven et al., 2010).

Though the isokinetic knee strength test may adequately evaluate knee function, it lacks standardization. The angular velocity, range of motion, and number of knee extension/flexion cycles reported in previous studies can vary, which makes it challenging to compare previous research (Keays et al., 2000; Lephart et al., 2002; Mattacola et al., 2002; Wilk et al., 1994). To properly understand this relationship, the isokinetic knee strength test needs to be conducted consistently.

A more consistent maximal effort test of knee function is the single-leg horizontal hop test (Gustavsson et al., 2006). This test is performed by hopping forward from a single-leg, as far as possible, and landing on the same leg. The leg symmetry of the patient’s hop distance is related to their subjective knee function and widely used by clinicians to judge when patients are ready to return to physical activity after ACLR (Myer et al., 2006; van Grinsven et al., 2010; Werstine, 2009; Wilk et al., 1994).
Unfortunately, the single-leg horizontal hop and isokinetic knee strength tests cannot be performed throughout ACLR rehabilitation and could be feared by patients. During and after rehabilitation, a fear of re-injury is prominent, and it can persist after rehabilitation is completed (Ardern et al., 2011; Chmielewski et al., 2008; Kvist et al., 2005). Since maximal effort tests of knee function require high demands on the knee, including maximal strength and maximal power, a fear of re-injury may confound a patient’s performance on these tests. Also, these maximal effort tests place a high demand on the ACL-reconstructed knee that is contraindicated early in rehabilitation (Cascio et al., 2004; Lahav & Burks, 2005). Therefore, an evaluation of early-rehabilitation dynamic knee function is not currently conducted. Measuring early rehabilitation knee function is important in order to understand a patient’s readiness to perform more demanding movements. Though speculative, early knee function measurement may also estimate which patients will be ready for return-to-activity testing after rehabilitation; patients who recover their knee function quicker may more likely pass return-to-activity tests and return to sport. But in order to evaluate such an idea, clinicians need to measure knee function objectively throughout rehabilitation with less demanding movement tasks.

2.2.4 Sub-Maximal Effort Tests

If maximal effort tests are too demanding for the patient, knee function can be evaluated with sub-maximal effort tests. These tests are not as common as maximal effort tests in the literature. Previous studies have evaluated knee function sub-maximally with the joint position sense, forward lunge and step-up-and-over tests (Alkjaer, Henriksen, Dyhre-Poulsen, & Simonsen, 2009; Alkjaer, Simonsen, Peter Magnusson, Aagaard, & Dyhre, 2002; Chmielewski et al., 2002; Harter et al., 1988; Lin et al., 2010; Mattacola et al., 2004).
1. *Joint position sense test.* The joint position sense test is commonly performed by passively moving the shank from its starting position to a test position in reference to the thigh, passively restoring the starting position, then asking the individual to recreate the test position (Harter et al., 1988). By blinding the individual to the positioning, the test can assess knee joint proprioception. While proprioceptive training is important in ACLR rehabilitation, much of the evidence suggests that performance on the joint position sense test is unrelated to overall knee function and not clinically relevant (Gokeler et al., 2012; Harter et al., 1988).

2. *Forward lunge test.* The forward lunge test is performed by stepping forward onto a force plate with the lead leg, flexing the knee to 90°, then extending the knee to return to the original standing position (Alkjaer et al., 2009, 2002; Mattacola et al., 2004). Measures of knee extensor moment, impact index and movement time can assess differences between the involved and uninvolved legs of patients with ACL injuries, patients with ACLR, and between patient and ACL-intact populations (Alkjaer et al., 2002; Mattacola et al., 2004).

3. *SUAO test.* The SUAO test is performed on a force plate by stepping up onto a 305 mm high box with the lead leg, carrying the body over the box, and landing with the trail leg contacting the force plate on the opposite side of the box (Chmielewski et al., 2002; Lin et al., 2010; Mattacola et al., 2004). Measures of Lift Index, Impact Index and Movement Time from the test can assess differences between the involved and uninvolved legs of patients with ACL injuries, patients with ACLR, and between patient and ACL-intact populations (Chmielewski et al., 2002; Lin et al., 2010; Mattacola et al., 2004).

The forward lunge and SUAO tests may be two methods of assessing sub-maximal knee function. Each have clear measures that score ACL-intact individuals, ACL-injured patients, and ACL-reconstructed patients differently. Currently, the tests evaluate knee function using expensive laboratory equipment that may be unavailable in the clinic.
2.2.5 Obstacles with Clinical Testing During ACL Rehabilitation

In the clinic there are obstacles that restrict the implementation of a dynamic, lab-based test of knee function. As previously discussed, some tests are highly demanding; these tests may be feared and cannot be used early in rehabilitation. Another obstacle for many clinics, not yet discussed, is the test’s cost. Expensive devices, such as the force plate used for the forward lunge and SUAO tests, may not be affordable for many clinics. Clinics do require an objective measurement tool like the force plate for their sub-maximal effort tests, but either the device’s cost must decrease or an inexpensive alternative must be considered if clinicians are to use these tests. Other barriers to a test’s implementation include its time to administer, time to score, and interpretability. Therefore to be implemented, tests must consider the needs of the clinic.

Clinical needs are satisfied partly, but not completely by current tests. Patient questionnaires require a patient’s evaluation of their own knee, which is subjective. Manual tests require the clinician to judge their application of force and reading of knee joint laxity, which is subjective. Maximal effort tests are objective, but a patient’s fear of re-injury may confound the results on these tests, and the tests cannot be completed early in rehabilitation because of their high mechanical demand on the knee. Sub-maximal effort tests, like the forward lunge and SUAO tests, are less demanding on the knee than maximal effort tests, but also require force plates to perform, which are expensive. No test is currently objective, of low demand and inexpensive.

2.3 Using Wearable Sensors as ACLR Rehabilitation Tools

To decrease the expense of the sub-maximal tests of knee function, one could consider alternatives to a force plate, such as wearable sensors. A possible sensor is an accelerometer. A 3-axis, wireless accelerometer and signal transmitter/receiver, such as YEI Technologies’ Wireless Sensor and Dongle (2015), can be used to accurately estimate segment and joint
kinematics (Mizuike, Ohgi, & Morita, 2009; Moe-Nilssen, 1998). At 363 USD, the accelerometer can be purchased for far less than portable force plates. As an example, a typical portable force plate package retailed by Bertec Corporation, including the force plate, amplifier and connecting cables, costs 11,391.60 USD (Appendix A). This amount includes a large discount that can be negotiated in package deals, yet the amount exceeds that of accelerometers by over 30 times. Accelerometers provide a substantial cost savings that may appeal to many clinicians.

Clinicians can use accelerometers to measure knee kinematics in sub-maximal tests of knee function, but accelerometers cannot measure knee kinetics. A measurement of the knee’s kinetics also requires ground reaction forces (Mattacola et al., 2004). However, the Lift Index and Impact Index measures from the SUAO test, obtained from ground reaction forces, are simply weight-normalized forces, accelerations, that can be measured by a single accelerometer. Therefore, a single accelerometer may make the SUAO test available to clinicians for routine use as an objective, low demanding and inexpensive test of knee function.
Chapter 3

Thesis Objectives

A. Discover if an accelerometer is a valid alternative to a force plate for the SUAO test (Chapter 4).

B. Determine if the SUAO test, with an accelerometer, is performed differently by ACL-intact individuals and ACLR patients (Chapter 5).

C. Determine if a relationship exists between SUAO test performance and subjective knee function (Chapter 5)
Chapter 4

Manuscript A (in press with Journal of Applied Biomechanics)

An accelerometer as an alternative to a force plate for the step-up-and-over test.

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Both authors were fully involved in the study and preparation of the manuscript. The material within will not be submitted for publication elsewhere.
4.1 Abstract

The step-up-and-over test has been used successfully to examine knee function after knee injury. Knee function is quantified using the following variables extracted from force plate data: the maximal force exerted during the lift, the maximal impact force at landing and the total time to complete the step. For various reasons, including space and cost, it is unlikely that all clinicians will have access to a force plate. The purpose of the study was to determine if measurements of the step-up-and-over test could be simplified by using an accelerometer.

The step-up-and-over test was performed by 17 healthy young adults while being measured with both a force plate and a three-axis accelerometer mounted at the low back.

Results showed that the accelerometer and force plate measures were strongly correlated for all three variables \( r = .90-.98, P < .001 \), that the accelerometer values for the Lift and Impact Indexes were 6-7% higher \( P < .01 \) and occurred 0.07-0.1 s later than the force plate \( P < .05 \). The accelerometer returned values highly correlated to those from a force plate. Compared to a force plate, a wireless, 3-axis accelerometer is a less expensive and more portable system with which to measure the step-up-and-over test.

Keywords: accelerometer; step-up-and-over test; knee function

Word Count: 1879
4.2 Introduction

Objective measures of knee function, such as force, joint moment or motion symmetry, can evaluate changes in knee function after injury, through the rehabilitation process and upon releasing patients to return to their regular activities (Alkjaer et al., 2009; Augustsson et al., 2004; Ford et al., 2003; Gustavsson et al., 2006; Myer et al., 2006). However, objective measures can require expensive and sophisticated equipment including force plates, motion tracking systems and devices to measure muscle activation. So, while many tests measure knee function (Alkjaer et al., 2009; Augustsson et al., 2004; Ford et al., 2003; Gustavsson et al., 2006; Myer et al., 2006), due to expense and availability, few are routinely available to the clinician. The development of body-worn sensors provides the opportunity to measure knee function using much less expensive systems with the added benefit of being able to capture this data outside of the laboratory, that is – in a clinical setting. An inexpensive, accessible, objective test of knee function would be a useful tool in clinical decision making.

One assessment of knee function that could be used in clinical decision making is the step-up-and-over (SUAO) test. To execute the SUAO test, the participant stands on a force plate behind a 305mm high box. They step up onto the box with their lead leg, carry their body over the box, and land with their trail leg contacting the force plate on the opposite side of the box, completing the test (Chmielewski et al., 2002; Lin et al., 2010; Mattacola et al., 2004). This is a good candidate test as it requires a submaximal effort and can therefore be used throughout rehabilitation.

Three variables are extracted from the force plate data: the Lift Index, Impact Index and Movement Time. The Lift Index is the maximal vertical force recorded as the body is raised up onto the box divided by the participant’s body weight, and characterizes the concentric control of the lead leg’s knee extensors. The Impact Index is the maximal vertical force recorded at the
touch-down of the trail leg divided by the participant’s body weight and characterizes the eccentric control of the lead leg’s knee extensors. Movement Time is the time from the initiation of movement until touch-down of the trail leg and includes both the concentric and eccentric phases of the knee’s extensors. These measures differ between patients with ACL injuries and a healthy population (Chmielewski et al., 2002; Lin et al., 2010; Mattacola et al., 2004).

Previous work investigating the SUAO test has used a force plate to quantify ground reaction forces, and for many clinics the expense, size, and power outlet requirement of the force plate may be barriers to the test’s implementation. A less expensive, smaller, self-powered option may help to facilitate clinical use of the SUAO test and allow for collecting important, objective kinetic data to quantify lower extremity function. Since the Impact Index and Lift Index are force values divided by a mass they are accelerations and, as for Movement Time, motion requires acceleration. Therefore, our purpose was to determine if measurements of the SUAO test could be completed using an accelerometer. Our hypothesis is that the Impact Index, Lift Index and Movement Time as measured by the force plate and accelerometer are highly correlated.

4.3 Methods

Seventeen healthy young adults (age: 23 ± 3 y; mass: 68 ± 10 kg; height: 1.74 ± 0.10 m) with no prior knee surgeries and no current lower limb injuries participated in the study. The study was approved by the University’s Research Ethics Board and all participants signed a letter of informed consent.

For testing, an accelerometer (Trigno Wireless, Delsys Inc., Natick, MA, USA; range = ± 6 g; sampling frequency = 148.1 Hz) (see Appendix B for frequency content during SUAO test) was taped onto a rigid piece of plastic before being secured with a Velcro strap over the spinous process of the L3 vertebra as an estimate of the center of mass location (Moe-Nilssen, 1998),
with the accelerometer's x-axis aligned vertically. The accelerometer’s 96 ms delay was
corrected for before data collection using the motion capture software (Qualisys Track Manager,
Qualisys, Gothenburg, Sweden). A 305mm high box was placed on the force plate (BP6001200,
AMTI, Watertown, MA, USA; sampling rate = 1000 Hz) and the participant stood quietly on the
force plate in front of the box to begin testing. Each participant performed five trials of the
SUAO test (see Appendix C for calculation of required number of trials), as described in the
introduction, at a comfortable pace and the leg tested (i.e. the lead leg) was chosen at random.

Analysis for both devices was done in Matlab (R2011B, The MathWorks Inc., Natick,
MA, USA). To time synchronize the devices, all accelerometer data was up-sampled to 1000 Hz
using Matlab’s ‘resample’ function. Both data sets were filtered using a second order, dual-pass,
low-pass Butterworth filter with a 20 Hz cutoff frequency. The body weight index (BWI),
commonly used to report SUAO test results, was then computed by subtracting body weight
from the vertical ground reaction force then dividing by body mass and then multiplying the
result by 100. For the accelerometer, one g was subtracted from the accelerometer data and then
multiplied by 100 to compute the same BWI, which was simply the acceleration change from
quiet standing. Lift Index, Impact Index and Movement Time were extracted from both the
acceleration and force plate BWI data sets. The Lift Index was the peak value during the up-
phase of the step while the Impact Index was the peak value during the down-phase of the step.
These peaks occurred at the Lift Time and Impact Time. Movement Time was the time from the
Weight Shift Time to the Impact Time, where the Weight Shift Time was defined as the first
instance that the absolute value of the BWI exceeded 5% of its maximum. This threshold was
selected as it was the lowest value that provided a stable measure of Weight Shift Time.

All analyses were done using SPSS (V20, IBM Corporation, Armonk, NY, USA).
Pearson's correlation analyses were performed to determine the relationship between the
accelerometer and force plate measured Lift Index, Impact Index and Movement Time, while paired t-tests assessed the differences between the devices. Paired t-tests were also used to assess whether there were differences between the devices for Lift Time, Impact Time and Weight Shift Time, which may reflect time delays due to the proximal location of the body-worn accelerometer. All variables for both devices met the assumptions of normality and homogeneity using Shapiro-Wilkes and Levene's tests. The significance threshold for all statistical tests was set at $P < .05$.

### 4.4 Results

The data profiles from the accelerometer and force plate were qualitatively similar in shape and magnitude (Figure 4.1). There were strong correlations between the accelerometer and force plate for Lift Index ($r = .98$, $P < .001$), Impact Index ($r = .97$, $P < .001$) and Movement Time ($r = .90$, $P < .001$) (Table 4.1). The paired t-tests indicated that the accelerometer measured a larger Lift Index ($P = .001$) and Impact Index ($P = .004$) than did the force plate (Table 4.1). In addition, the accelerometer measured later Lift and Impact Times than the force plate ($Ps < .05$) (Table 4.2).
Figure 4.1. A representative trial of the SUAO test displaying the body weight indexes measured by the accelerometer (grey line) and the force plate (black line) over time. The body weight index from the accelerometer was calculated by subtracting 1 g from the recorded acceleration, then multiplying by 100, and the body weight index from the force plate was calculated by subtracting the individual's body weight from the recorded force, then dividing by body weight and multiplying by 100. Also displayed are the Weight Shift (WS), Lift (L) and Impact (I) times.
Table 4.1. Means and standard deviations (Mean (SD)), and correlations of the accelerometer and force plate Lift Index, Impact Index and Movement Time.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Accelerometer Mean (SD)</th>
<th>Force Plate Mean (SD)</th>
<th>P (Paired T-Test)</th>
<th>r</th>
<th>P (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift Index (BWI)</td>
<td>74 (21)</td>
<td>67 (15)</td>
<td>.001*</td>
<td>.98</td>
<td>&lt; .001*</td>
</tr>
<tr>
<td>Impact Index (BWI)</td>
<td>98 (30)</td>
<td>92 (28)</td>
<td>.004*</td>
<td>.97</td>
<td>&lt; .001*</td>
</tr>
<tr>
<td>Movement Time (s)</td>
<td>1.82 (0.24)</td>
<td>1.80 (0.24)</td>
<td>.7</td>
<td>.90</td>
<td>&lt; .001*</td>
</tr>
</tbody>
</table>

BWI: Body Weight Index  
* Significant at P < 0.05

Table 4.2. Mean differences and standard deviation (Mean (SD)) of the accelerometer and force plate Lift, Impact and Weight Shift Time.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean Difference (Accelerometer - Force Plate)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift Time (s)</td>
<td>0.1 (0.06)</td>
<td>&lt; .001*</td>
</tr>
<tr>
<td>Impact Time (s)</td>
<td>0.07 (0.1)</td>
<td>.012*</td>
</tr>
<tr>
<td>Weight Shift Time (s)</td>
<td>0.05 (0.1)</td>
<td>.076</td>
</tr>
</tbody>
</table>

* Significant at P < 0.05

4.5 Discussion

As hypothesized, there were strong correlations between the accelerometer and force plate-measured variables of the SUAO test, suggesting that an accelerometer could be used as a simple, low-cost replacement for a force plate. However, the accelerometer measured larger Lift and Impact Indexes than the force plate, which was due to how the accelerometer data were
processed. In the SUAO test described in the literature, measures are taken from the force plate’s vertical axis, which was done here (Chmielewski et al., 2002; Lin et al., 2010; Mattacola et al., 2004). The force plate is stable so its vertical component is always vertical, however, since the accelerometer is attached to the participant, its orientation changes during movement. In addition, it is difficult to locate the accelerometer on the participant so that one axis is perfectly vertical. To overcome problems with orientation, either during placement or while moving, the net acceleration, rather than the acceleration along a single axis, was chosen as the outcome measure (Appendix D). The advantage of using the net acceleration is that the accelerometer does not require strict placement, reducing errors from a misalignment of the accelerometer when mounting it on a participant, thus simplifying its use. The disadvantage is that small accelerations in the transverse plane are included which increases the measurement (Appendix E). Since the overestimation worsened at high Lift and Impact Indices, the development of a methodological strategy or analytical computation is recommended to correct the overestimation. It is important to note that this small overestimation is specific for the SUAO test; other different and/or demanding sub-maximal tests may result in larger overestimations. Despite the inflated acceleration, the accelerometer and force plate variables remained highly correlated.

In addition to the different Lift and Impact Index magnitudes, there were different Lift and Impact Times between the accelerometer and force plate. The delayed measurement of the lift and impact by the accelerometer indicate that it quantified motion from the SUAO test later than the force plate. Likely contributing to the delayed measurements is the force transmission from the foot to the back. This transmission is not instantaneous across all joints of the lower limb, so it requires a small amount of time. Since the time can be a factor when evaluating an individual's motor control, such investigations should carefully consider the device's position when timing measures are critical.
The movement time reported here is longer than that reported by others (Chmielewski et al., 2002; Lin et al., 2010; Mattacola et al., 2004). This is due to a change in the instructions given on how to execute the SUAO test. Previous researchers asked participants to step as quickly as possible while we asked them to step at a comfortable pace, which reduces the intensity of the test. When testing patients with ACL injuries, especially pre-surgical or early in the rehabilitation process, the patient’s fear of re-injury (Chmielewski et al., 2008; Kvist et al., 2005) may alter the test results. A comfortable pace should reduce patient fear and may increase the circumstances under which the test can be used.

Other locations for the accelerometer were considered, including the hip, mid shank or foot of the trail leg (Appendix F). An accelerometer at these locations would likely reduce the time delay after the force plate. However, pilot testing showed that the accelerometer lift and impact indexes were less accurate than at the back. An additional consideration was that isolating the accelerometer on one leg meant that either a second accelerometer would be needed to test the other leg or that the other leg would have to be refitted to complete the test. The selected single location on the low back gave results for all three variables and can be used to test either leg.

In conclusion, for the SUAO test, the accelerometer was a smaller, less expensive and more portable alternative to a force plate. Considering this, clinicians may find that the accelerometer is a useful tool when evaluating knee function with the SUAO test.
Chapter 5

Manuscript B (to be submitted to Clinical Biomechanics)

Using an accelerometer and the step-up-and-over test to evaluate the knee function of patients with anterior cruciate ligament reconstruction.

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5.1 Abstract

Evaluating the dynamic knee function of patients after anterior cruciate ligament reconstruction (ACLR) is a challenge. A variety of objective tests have been developed, but for various reasons, few are regularly used in the clinic. A more practical test to use may be the step-up-and-over (SUAO) test. The test, with an accelerometer, is inexpensive and easy to conduct, and may be performed differently by ACLR patients and healthy individuals.

A control group (N = 26) and an ACLR group (N = 25) completed questionnaires to quantify subjective knee function and fear of re-injury, then completed the SUAO test.

Results showed that ACLR patients performed differently than controls for the SUAO test’s Lift Symmetry and Impact Symmetry (Ps < .05). Performance on these measures was related to the participant’s subjective knee function (ρ = -.46, P < .01; ρ = -.33, P < .05). Supplemental results for individual leg performance and the patient’s fear of re-injury are also reported and discussed. It seems that the SUAO test is performed differently by ACLR patients and healthy individuals, and that the performance is related to the person’s opinion of their knee’s function.

Keywords: step-up-and-over test, anterior cruciate ligament reconstruction, rehabilitation, knee function
5.2 Introduction

The rehabilitation following anterior cruciate ligament reconstruction (ACLR) is a challenging process to evaluate. The challenge begins with describing and understanding an ACLR patient’s knee function. Knee function is multi-factorial, but can be characterized partly by a patient’s post-surgical deficits. After ACLR, patients have deficits for range of motion, gait, proprioception, cardiovascular fitness and muscular strength (Myer et al., 2006; Shelbourne & Nitz, 1990; van Grinsven et al., 2010; Werstine, 2009). Therefore, these parameters should be assessed for improvement during rehabilitation in order to understand when the patient is able to return to full physical activity. The current evaluation methods are, at least in part, unsuccessful. Many patients are unable to return to their pre-injury physical activity level (Fithian, 2005; Kvist et al., 2005) and those that do are at an increased risk of tearing their graft or their contralateral anterior cruciate ligament (ACL) (Paterno et al., 2010; Pinczewski et al., 2007; Salmon et al., 2005; Wright et al., 2007). Better outcomes may come with changes to the current ACLR rehabilitation evaluation practice.

In the current practice, one of the frequently used evaluation methods of a patient’s knee function is a patient-completed questionnaire. Questionnaires, such as the widely-used International Knee Documentation Committee’s Subjective Knee Form (IKDC-SKF) (Irrgang et al., 2001), can effectively measure a patient’s symptoms, activity level and general knee function. A positive patient-reported result is one important part of an ACLR evaluation. However, this evaluation method is subjective and while the patient’s opinion of their knee is important, clinicians also require objective measures of knee function.

A widely used objective measure of knee function is a patient’s time since surgery. Often, a time since surgery of greater than or equal to six months is used to decide when a patient is ready to return-to-activity (Barber-Westin & Noyes, 2011). In fact, in the review by Barber-
Westin and Noyes (2011), time since surgery was a return-to-physical activity criterion in 60% of the ACLR rehabilitation studies, and the only criterion used in 32% of the studies. These proportions are alarmingly high considering the suggestion that time since surgery is a poor criterion (Barber-Westin & Noyes, 2011). More concerning is that objective measures, which could be used instead of or in conjunction with time since surgery, have been developed but are not frequently used. Alternative tests that objectively assess knee function include single-leg hopping (Gustavsson et al., 2006), jumping and landing (Ford et al., 2003), knee extension and flexion (Keays et al., 2000; Lephart et al., 2002; Mattacola et al., 2002; Wilk et al., 1994), lunging (Alkjaer et al., 2009, 2002; Mattacola et al., 2004) and stepping exercises (Chmielewski et al., 2002; Lin et al., 2010; Mattacola et al., 2004), but these tests have only been used in 16% of studies (Barber-Westin & Noyes, 2011). The reasons why these valid, objective tests are not used in clinical evaluation more often are unclear.

One reason may be the high physical demand of the tests. Activities that place high loads on the recovering knee create the fear of re-injury in some patients and this fear can be present both during and after rehabilitation (Ardern et al., 2011; Chmielewski et al., 2008; Kvist et al., 2005). Should the knee’s evaluation require highly demanding evaluations like the single-leg hop (Gustavsson et al., 2006), drop vertical jump (Ford et al., 2003), and isokinetic knee strength tests (Keays et al., 2000; Lephart et al., 2002; Mattacola et al., 2002; Wilk et al., 1994), the patient’s fear of re-injury may be a confounding variable in the evaluation. If fear of re-injury alters the evaluation’s performance, then the evaluation’s outcome does not accurately reflect knee function.

Besides the physical demand of the evaluation, cost and complexity may be other reasons why objective testing is not more widely used. The high cost of the motion capture systems and force plates required for some tests are unreasonable for many clinics. For example, several
typical outcome measures from the forward lunge test require both a motion capture system and a force plate. In addition there is the technical expertise to setup, run and maintain the equipment as well as process the data to produce the evaluation measures. Considering fear of re-injury, cost and complexity, a good knee function evaluation test would have low demand, be based on inexpensive equipment and be simple to operate.

The step-up-and-over (SUAO) test is one that simulates stair climbing and is less demanding than many proposed knee function tests. It involves navigating a single step and requires concentric knee control to step-up and eccentric control to step-down (Bailey & Costigan, 2015; Chmielewski et al., 2002; Lin et al., 2010; Mattacola et al., 2004). Most studies of the SUAO test have used a force plate (Chmielewski et al., 2002; Lin et al., 2010; Mattacola et al., 2004), but there is recent evidence that a criterion-valid alternative to the force plate is a single 3-axis accelerometer (Bailey & Costigan, 2015). A single force plate with its amplifier and cables can cost more than 10,000 USD (Appendix A) while accelerometers can be purchased for as low as 363 USD (YEI Technology, 2015). With the vast reduction in cost, the SUAO test, with an accelerometer, may be an evaluation that is objective, of low demand, inexpensive and simple to operate.

The SUAO test, with an accelerometer, has not yet been used to evaluate the knee function of ACLR patients. Knee function on the SUAO test is characterized by the level of knee extensor motor control exhibited by the lead leg. The performance of ACLR patients and ACL-intact individuals was different on the SUAO test when measured with a force plate (Chmielewski et al., 2002; Mattacola et al., 2004), but it is unknown if the same will be true when measured with an accelerometer. Regardless of the measurement device, it is unknown if SUAO test performance and subjective knee function are related. A relationship between SUAO test performance and subjective knee function would provide evidence that the test is clinically
relevant. Therefore, this study had two main objectives: first, to establish whether or not patients with ACLR performed differently on the SUAO test than individuals with ACL-intact knees, and second, to determine if a participant’s performance on the SUAO test was related to their subjective knee function.

5.3 Methods

5.3.1 Participants

A control group and an ACLR group were recruited. The control group had to have a current activity level $\geq 5$ on the Tegner Activity-Level Scale (Appendix G) and the ACLR group a pre-injury Tegner activity score $\geq 5$, indicating a high level of physical activity (Tegner & Lysholm, 1985). In addition, all participants had to be free from current injuries of the lower limbs and back, besides the ACL for ACLR patients. According to an a priori sample size computation (Appendix H), 26 participants were needed in each group. In total, 26 ACL-intact individuals were recruited to the control group and 26 ACLR patients to the ACLR group, with 1 ACLR drop-out from the study. Of the 25 ACLR patients remaining, 17 received a semitendinosus and gracilis graft while 8 received a bone-patella-bone graft, and the median time since surgery of all patients was 5.6 months (SD: 2.6; range: 1.3 – 9.2). All participants gave informed consent to participate in the study (see Appendix I for the letter of information and ethics consent forms).

5.3.2 Procedure

Questionnaires. Following informed consent, the participants completed the IKDC-SKF (Appendix J). This questionnaire is a valid and reliable measurement of subjective knee function (Irrgang et al., 2001). The ACLR group also completed the TSK-11 (Appendix K) to provide a valid and reliable measurement of the fear of re-injury (George, Lentz, Zeppieri, Lee, &
Chmielewski, 2012). Five patients did not complete the questionnaires, reducing the sample sizes for the IKDC-SKF (N = 46) and TSK-11 (N = 20). All questionnaires were coded by the principle investigator to ensure participant privacy and, once completed, were locked in a secure location.

*Instrumentation.* After completing the questionnaires, participants were instrumented with a 3-axis, wireless accelerometer (3-Space Wireless Sensor, YEI Technology, Portsmouth, OH, USA) secured with a Velcro strap on the spinous process of the L3 vertebra, which approximates the participant's center of mass location (Moe-Nilssen, 1998). From this position, the accelerometer returns criterion-valid measures from the SUAO test (Bailey & Costigan, 2015). The accelerometer was collected at 200 Hz, which was sufficient for the SUAO test (Appendix B), by the 3 Space Suite software program (V3.0r9, YEI Technology, Portsmouth, OH, USA). Once the accelerometer’s position was secured with a Velcro strap, participants were ready to perform the SUAO test.

*SUAO test.* The SUAO test was performed on a level floor with a 305mm high box. Participants began standing behind the box; they stepped up on the box with the lead leg, carried the body and trail leg over the box, and landed with the trail leg contacting the floor on the other side of the box (Bailey & Costigan, 2015; Chmielewski et al., 2002; Lin et al., 2010; Mattacola et al., 2004). Participants were instructed to complete the SUAO test at a self-selected, comfortable pace. While the SUAO test has been previously performed at maximum speed (Chmielewski et al., 2002; Lin et al., 2010; Mattacola et al., 2004), a slower pace requires less effort and may be safer. For controls, the lead leg was either the dominant or non-dominant leg and for ACLR patients the lead leg was either the involved or uninvolved leg. Five trials were completed by each leg and the order of all 10 trials was randomized.
5.3.3 Analysis

The SUAO test measures refer to the performance of the participant’s lead leg. From the lead leg’s performance, Lift Index, Impact Index and Movement Time measures were extracted from the net acceleration profile of the accelerometer using a custom Matlab program (R2011B, The MathWorks Inc., Natick, MA, USA). The Lift and Impact Indices were mass-normalized and unit-less measures that characterized the concentric and eccentric control of the lead leg’s knee at the SUAO test’s lift and impact phases, respectively, and Movement Time characterized both the concentric and eccentric control. The method used to calculate these measures was described previously (Bailey & Costigan, 2015). The Lift Indices, Impact Indices and Movement Times measures were averaged for each leg in each participant so that there was one value per measure for each of the two control legs, the ACLR involved leg and the ACLR uninvolved leg.

After averaging the trials for each leg by participant, the limb symmetry index (LSI) was calculated to determine each participant’s limb symmetry. For controls, the LSI was calculated by dividing the non-dominant leg score by the dominant leg score, then multiplying by 100. For ACLR patients, the LSI was calculated by dividing the involved leg score by the uninvolved leg score, then multiplying by 100. LSIs were calculated for Lift Index, Impact Index and Movement Time, giving 3 new variables: Lift Symmetry, Impact Symmetry and Movement Time Symmetry. For these variables, a score of 100 indicated perfect symmetry and scores deviating from 100 were increasingly asymmetric.

All statistical tests were performed using SPSS (V20, IBM Corporation, Armonk, NY, USA). Because, as a group, the ACLR patients’ SUAO test performance was not normally distributed (Appendix L), non-parametric statistical tests were performed. First, Mann-Whitney U tests were conducted to compare the control and ACLR groups’ medians for Lift Symmetry, Impact Symmetry and Movement Time Symmetry (Objective 1). The effects of different group
characteristics on limb symmetry were included and controlled for if necessary. A correlation analysis (Spearman’s rho ($\rho$)) then tested for relationships between the symmetry measures and time since surgery, and subjective knee function.

In addition to the analysis of the symmetry measures, subsequent correlation analyses (Spearman’s rho ($\rho$)) were conducted to explore the relationships between the Lift Index, Impact Index and Movement Time Symmetries and the fear of re-injury. As well, Lift Index, Impact Index and Movement Times were compared between the ACLR patients’ involved leg and a random control leg, and the ACLR patients’ uninvolved leg and a random control leg using Mann-Whitney U tests. For all statistical tests, the threshold for significance was set at $P < .05$.

5.4 Results

The results showed that ACLR patients had larger Lift Symmetry and Impact Symmetry scores than the controls, with a median LSI of $128.9 \pm 40.7$ and $151.4 \pm 52.4$ for Lift Symmetry and Impact Symmetry, respectively, compared to the control group’s medians of $97.2 \pm 16.8$ and $101.7 \pm 16.0$ ($Ps < .001$) (Figure 5.1). Movement Time Symmetry was not significantly different between the groups ($P = .53$). The control and ACLR groups also differed in age ($P = .006$) and mass ($P = .001$) (Table 5.1), and relationships existed between age and Impact Symmetry ($\rho = .50$, $P < .001$), mass and Lift Symmetry ($\rho = .39$, $P = .02$), and mass and Impact Symmetry ($\rho = .32$, $P = .005$). With age and mass as covariates, rank analyses of covariance (Quade, 1967) found that the control and ACLR groups still had different Lift Symmetries ($F (1,49) = 12.5, P = .003$) and Impact Symmetries ($F (1,49) = 9.9, P = .001$).
Figure 5.1. Limb Symmetry Indices recorded by the control (dark grey) and ACLR (light grey) groups for Lift, Impact and Movement Time Symmetries. Asterisks indicate significant differences at \( P < .05 \).

Table 5.1. Control and ACLR group characteristics. Values are medians (SD) unless otherwise specified.

<table>
<thead>
<tr>
<th>Participant Characteristic</th>
<th>Control (n = 26)</th>
<th>ACLR (n = 25)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td>13 male, 13 female</td>
<td>16 male, 9 female</td>
</tr>
<tr>
<td>Age (years)</td>
<td>21 (5)</td>
<td>27 (10)*</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.75 (0.09)</td>
<td>1.77 (0.12)</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>73.5 (13.0)</td>
<td>83.0 (17.8)*</td>
</tr>
<tr>
<td>Activity level</td>
<td>7 (2)</td>
<td>8 (1)</td>
</tr>
</tbody>
</table>

* \( P < 0.05 \)
For the ACLR group, negative correlations were found between subjective knee function score and the Lift and Impact Symmetries ($\rho = -0.72, P < .001; \rho = -0.49, P = .001$) (Figure 5.2) (Objective 2). Though Impact Symmetry was not correlated to time since surgery ($P = .83$) Lift Symmetry was ($\rho = -0.60, P = .001$), and there was a strong positive correlation between subjective knee function and time since surgery ($\rho = .71, P < .001$) (Figure 5.3).

Figure 5.2. The relationship between ACLR patient subjective knee function score on the IKDC-SKF and Lift Symmetry (A) and Impact Symmetry (B). The linear best fits (grey dashed lines) are shown and Spearman's rho coefficients ($\rho$) are displayed in the top right corners of each graph.
Figure 5.3. The relationship between ACLR patient time since surgery and subjective knee function score on the IKDC-SKF. The linear best fit (grey dashed line) is shown and Spearman’s rho ($\rho$) is displayed in the bottom right corner of the graph.

In addition to the group differences in limb symmetry, Lift Index and Impact Index, the raw measures that go into the symmetry calculations, were lower in the uninvolved leg than in the control leg ($P = .003; P = .001$ respectively) (Table 5.2). As well, Movement Time was longer for both the involved and uninvolved legs than for the control leg ($P = .017; P = .035$ respectively).
Table 5.2. Median (SD) Lift Index, Impact Index and Movement Time when the lead leg of the SUAO test is a control, involved or uninvolved leg.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Control Leg</th>
<th>Involved Leg</th>
<th>Uninvolved Leg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift Index</td>
<td>75.2 (23.3)</td>
<td>81.5 (27.8)</td>
<td>62.2 (21.2)*</td>
</tr>
<tr>
<td>Impact Index</td>
<td>121.7 (28.1)</td>
<td>139.2 (45.6)</td>
<td>104.1 (18.4)*</td>
</tr>
<tr>
<td>Movement Time (s)</td>
<td>2.15 (0.25)</td>
<td>2.37 (0.34)*</td>
<td>2.33 (0.34)*</td>
</tr>
</tbody>
</table>

* P < .05 compared to control leg

There was also an interesting phenomenon observed with the ACLR patients’ fear of re-injury. While fear of re-injury was related to subjective knee function (ρ = -.54, P = .01), fear of re-injury was not related to either Lift Symmetry or Impact Symmetry (P = .50; P = .90).

5.5 Discussion

The main results, fulfilling this study’s first objective, were that the ACLR group had higher Lift and Impact Symmetries than the control group. Since a score of 100 indicates perfect symmetry and the control group scored 97.2 and 103.8 for Lift Symmetry and Impact Symmetry, the ACLR group’s legs, with higher scores were less symmetric, an effect seen with other dynamic knee tests (Juris et al., 1997; Paterno et al., 2007; Thomeé et al., 2012; Wilk et al., 1994). With these measurements computed from accelerometer data, this study is the first to show that an objective, low demand and inexpensive test can detect symmetry differences between ACL-intact individuals and ACLR patients.

In addition, performance on the SUAO test was related to participant-reported knee function, as lower (and more symmetric) Lift and Impact Symmetries were related to higher subjective knee function scores (Objective 2). Evaluating subjective knee function is important to patients (Tanner et al., 2007), provides scores to clinicians that can be compared against normative values (Anderson, 2005), and is useful when making return-to-physical activity
decisions (Myer et al., 2006). With its relationship to subjective knee function, the SUAO test may be relevant to the clinical evaluation of ACLR patients.

An objective measure currently used in the clinical evaluation of an ACLR patient is their time since surgery. The relationship of time since surgery to SUAO test performance in this study was unclear. While Lift Symmetry was correlated to time since surgery, Impact Symmetry was not. There was, however, a clear relationship between time since surgery and subjective knee function in this study. Both time since surgery and subjective knee function are commonly used knee evaluations (Barber-Westin & Noyes, 2011) but as described previously, time since surgery may be a poor evaluation option (Barber-Westin & Noyes, 2011). The SUAO test is a new clinical option to consider.

The median limb symmetry measurements from the SUAO test were largely influenced by the uninvolved leg’s performance, an effect not seen previously. When the uninvolved leg was the lead leg, the Lift Index and Impact Index were lower than for the control leg, which disagrees with previous reports of the SUAO test (Chmielewski et al., 2002; Mattacola et al., 2004). Chmielewski and colleagues (2002) and Mattacola and colleagues (2004) did not find differences between the patient’s uninvolved leg and the control leg. Mattacola and colleagues (2004) also reported a larger Lift Index for the involved leg than for the control leg, another effect not seen in the current study. The low uninvolved leg Lift and Impact Indices could be a result of the focus on the involved leg during physical rehabilitation. The strength compensation of the uninvolved leg for the involved leg after ACL injury suggests that the uninvolved leg’s rehabilitation cannot be neglected (Laurie A Hiemstra et al., 2007), yet this may occur. As a result, patients may be more cautious with their uninvolved leg by lifting and lowering their body less forcefully on the SUAO test. However, the group result seen in the current study may not reflect individual results. On an individual basis, some patients performed as Chmielewski and
colleagues (2002) and Mattacola and colleagues (2004) have reported with higher Lift and Impact Indices on their involved legs than the control legs (Appendix M). It could be that the ACLR group’s means for Lift Index and Impact Index misrepresent some ACLR patients. The inter-patient differences suggest that performance on the SUAO test varies individually.

ACLR patients and controls also completed the SUAO test more slowly than in previous studies (Chmielewski et al., 2002; Lin et al., 2010; Mattacola et al., 2004). In the current study, median Movement Times for the involved, uninvolved and control legs were 2.37s, 2.33s and 2.15s respectively, and the longest Movement Times reported previously were 1.70s, 1.80s and 1.47s (Lin et al., 2010). The longer Movement Times in the current study are likely the result of altering the required effort level, which was lowered by instructing patients to complete the test at a comfortable pace. Interestingly, at a comfortable pace the SUAO test may be more suited for early-rehabilitation ACLR evaluation as high demand movements are contraindicated in the first 12 weeks of rehabilitation (Cascio et al., 2004; Lahav & Burks, 2005). An increased Movement Time reduces knee demand since a longer time is proportional to a lower force when assuming a constant impulse. The longer Movement Times in this study may make the SUAO test an early rehabilitation evaluation option, a necessity to evaluate ACLR patient knee function throughout rehabilitation.

The IKDC-SKF is another testing option that can be used throughout rehabilitation, but its scores were correlated to fear of re-injury. Previous studies have found that a patient’s fear of re-injury affects their perception of their knee’s function (Kocher et al., 2004; Wilk et al., 1994), so much so that it is a limiting factor that prevents patients from returning to their pre-injury physical activity level (Kvist et al., 2005). To evaluate knee function accurately it is important for clinicians to include tests that are unaffected by a patient’s fear of re-injury. The SUAO test is one such test, as Lift Symmetry and Impact Symmetry were not related to a patient’s fear of
re-injury. As fear of re-injury was unrelated to performance on the SUAO test, the test may be a more accurate physical evaluation tool than the IDKC-SKF.

Knee evaluation methods following ACLR is a current topic of discussion in the literature because dynamic tests are so infrequently used. As Barber-Westin and Noyes reported (2011), only 16% of ACLR rehabilitation studies evaluate knee function using dynamic tests. These dynamic tests provide objective information about a patient’s knee strength (Keays et al., 2000; Lephart et al., 2002; Mattacola et al., 2002; Wilk et al., 1994) and power (Ford et al., 2003; Gustavsson et al., 2006) that, with the subjective evaluation (Briggs et al., 2009; Daniel et al., 1985; Irrgang et al., 2001; Katz & Fingeroth, 1986; Woby et al., 2005), may provide a more comprehensive assessment of a patient’s knee function. The infrequent use of dynamic knee tests suggests that many may not be practical in the clinic. To be clinically practical, dynamic tests should include objective, low demand and inexpensive options, like the SUAO test. Further research should add the SUAO test to existing clinical evaluation methods to investigate if, together, they provide a more comprehensive assessment of ACLR patients.

5.6 Conclusion

In conclusion, the SUAO test is an objective, low demand and inexpensive method on which ACL-intact individuals and ACLR patients perform differently. Performance on the test is related to the patient’s opinion of their knee function and unaffected by their fear of re-injury. With the current need to evaluate ACLR patients with objective measures, the SUAO test may provide a new option that is practical for clinicians.
Chapter 6

General Discussion

Together, the results from Chapters 4 and 5 suggest that the SUAO test, executed using an accelerometer rather than a force plate, is an objective and practical method on which ACL-intact individuals and ACLR patients perform differently. Chapter 4 provides the support for replacing the force plate, currently used for the SUAO test, with an accelerometer. As a consequence of changing to an accelerometer, the method for extracting Lift Index, Impact Index and Movement Time were re-developed. Changing to an accelerometer decreases the cost of the test, reduces the equipment required, and increases portability making the test more accessible to the clinician.

While Chapter 4 suggests that an accelerometer is a criterion-valid alternative to a force plate, Chapter 5 evaluated ACLR patients using the modified hardware and software. The results were that ACLR patients performed differently on the SUAO test than ACL-intact individuals. Combining the results of Chapters 4 and 5, the conclusion is that ACL-intact and ACLR patient performance is different on the SUAO test, and when using an accelerometer, the test is objective and practical, important attributes for clinical use.

To assess the clinical viability of this version of the SUAO test, further research is needed to see if SUAO test scores improve as patient knee function improves. There was some evidence that improved knee function is related to improved SUAO limb symmetry measures. In Chapter 5’s cross-sectional study, both Lift Symmetry and Impact Symmetry were correlated with subjective knee function (IKDC-SKF). While these initial results are encouraging, testing patients as they progress through ACLR rehabilitation is required to evaluate if improvements in SUAO test scores are reflected by improvements in knee function.
The evaluation of individuals will be important since there is some evidence that ACLR patients may not all perform the same on the SUAO test, as seen in a case-study of individual patient results (Appendix M). Chapter 5 reported that the Lift and Impact Symmetries of the ACLR group were larger than the control group. However, since the symmetry measure is computed by dividing the involved leg’s score by the uninvolved leg’s score, the performance of both legs must be considered. When each ACLR leg was compared to the average control leg for Lift Index and Impact Index, several different cases emerged. The first and most common case was ACLR patients who performed “Normally”, much like controls. More interesting were the second and third most common cases. The second most common case was “High Involved”, where the involved leg lifted or impacted more forcefully than controls. Patients that fit the “High Involved” case, as discussed in Chapter 5, were misrepresented by the group’s average. In the third most common case, “Low Uninvolved”, the uninvolved leg lifted or impacted less forcefully than controls. Low results for the uninvolved leg suggest that these patients were cautious. When the uninvolved leg led, the involved knee flexed to clear the box during the lift, then absorbed the main impact. High flexion and loading are likely painful for the involved leg, so some patients may have been cautious when leading with their uninvolved leg. While “High Involved” and “Low Uninvolved” patients performed differently on the SUAO test, their Lift and Impact Symmetries were similar. Thus even with similar Lift and Impact Symmetries, there is a considerable amount of performance variability on the SUAO test among ACLR patients.

Individual variability was also seen within ACL-intact individuals (Appendix M). More controls were classified as “Normal” than ACLR patients for each measure. For Lift Index, Impact Index, and Movement Time, 81%, 62% and 46% of controls were classified as “Normal” respectively, compared to 36%, 44% and 20%. Even for controls, many individuals were not “Normal”. While variability can be expected within controls, the size of it may be amplified as it
is not currently known what constitutes a normal Lift Index, Impact Index, or Movement Time on the SUAO test. The test’s conditions for normal performance need to be explored to explain some of the variability seen among ACL-intact individuals and ACLR patients.

In addition to the ACLR patient variability, the cases also revealed that an ACLR functional performance may not be normal, even when the limb symmetry is very similar to a perfect value of 100. An example of this can be seen for Lift Index with the “Low Both” and “High Both” cases. In these cases, five patients lifted either less or more forcefully than controls for both their involved and uninvolved legs. Two of the five patients also still scored within 1 SD of the average control Lift Symmetry (103.8 ± 16.0) with scores of 105.7 and 118.8. Therefore, limb symmetry measures alone may misrepresent performance, a problem that may exist in other limb-symmetry-based knee evaluations (Barber-Westin & Noyes, 2011; van Grinsven et al., 2010). Therefore limb symmetry measures alone cannot guarantee that ACLR patients have recovered from their injury. While the cases are small in sample size, thus requiring further study, ACLR performance on the SUAO test is variable and, when only reporting limb symmetry results, misleading.

It is important to consider which results from the SUAO test should be reported. Limb symmetries are an easy to calculate, objective, and widely used measure for assessing return-to-physical activity readiness in ACLR patients (Gustavsson et al., 2006; Myer et al., 2006; van Grinsven et al., 2010; Werstine, 2009; Wilk et al., 1994). Yet as discussed, limb symmetries measures on their own may be misleading, requiring additional results from the SUAO test. The involved and uninvolved legs’ performances on the test can also be reported, yet no normative standards for Lift Index and Impact Index performance currently exist. Normative standards have been developed for a subjective knee function evaluation tool (Anderson, 2005) and, with the standards, the tool has been useful to clinicians for return-to-activity decisions (Myer et al.,
2006). It seems that limb symmetries provide easy to calculate and objective results from the SUAO test, but the test may be more meaningful if normative scores for the ACLR patient’s involved and uninvolved legs are also developed.

In addition to improving the evaluation of ACLR patient knee function, clinicians may need to address the patient’s fear of re-injury to improve clinical outcomes. ACLR rehabilitation is mainly physical (Myer et al., 2006; van Grinsven et al., 2010; Werstine, 2009) and not focused on reducing the patient’s fear of re-injury. Unfortunately, a patient’s fear of re-injury is one factor that limits their physical activity (Kvist et al., 2005), as it largely influences their opinion of their knee’s function (Kocher et al., 2004; Wilk et al., 1994). To combat the patient’s fear of re-injury, clinicians may need to consider combining their physical rehabilitation with behaviour counselling to reduce the fear of re-injury in injured individuals (Chase, Magyar, & Drake, 2005; Vlaeyen, De Jong, Geilen, Heuts, & Van Breukelen, 2001). Adding behaviour counselling to ACLR rehabilitation is a combined approach that may improve the proportion of patients that safely return to pre-injury physical activities.

The results of Chapter 5 in this thesis come with some important limitations that may guide further research. In Chapter 5, there was variability in the ACLR group’s characteristics. Besides the different age and mass than controls, patients had a wide range for time since surgery (1.3 – 8.8 months), different grafts, and unreported health histories. Differences for time since surgery, graft type and health history may lead to different performances, so it is unknown how these factors affect SUAO test performance. Another limitation of Chapter 5 was the study’s design. Due to this thesis’ time constraint, a cross-sectional design was selected. With the cross-sectional design, ACLR patients were able to be tested at different points in their rehabilitation, yielding large ranges for time since surgery and subjective knee function. With the large ranges, the relationship between SUAO test performance and subjective knee function became apparent.
The disadvantage of the cross-sectional study is that it is not known if the relationship is a cause-and-effect relationship. Understanding the cause-and-effect relationship, if there is one between knee function recovery and SUAO test performance, would provide valuable support for using the SUAO test to evaluate knee function. In spite of their limitations, the results from Chapter 5 suggest that testing for a cause-and-effect relationship is a logical next step.

In all, this thesis has contributed a new method to evaluate the knees of ACLR patients, one that is accessible to clinicians. Chapter 2 demonstrated that while many methods of evaluating knee function exist, none are objective, of low demand and inexpensive, all three necessary attributes for a clinical test. To address the need for a clinical test, an accelerometer device replaced the force plate in the SUAO test to make it inexpensive and the movement criterion changed from requiring maximal speed to moving at a comfortable speed (Chapter 4). This modified SUAO test was then used to assess the performance of ACL-intact individuals and ACLR patients, performance that was related to subjective knee function (Chapter 5). Together, Chapters 4 and 5 showed that the SUAO test is a clinically relevant method that is performed differently by ACL-intact individuals and ACLR patients. This discussion then described some of the current issues related to knee function evaluation such as performance variability in patients, which results to report and the influence of fear in test evaluation, all requiring further study. As a next step, clinicians should assess if improved performance on the SUAO test is related to the improvements that ACLR patients make during rehabilitation, to see if the SUAO test is a responsive knee evaluation tool.
References


Appendices
Figure A-1. Cost of a portable force plate ($8,085), analog to digital converter/amplifier ($2,871), and an amplifier output cable ($264).
Appendix B: SUAO Test’s Frequency Content

A Fast Fourier Transform was performed to find the SUAO test’s Nyquist frequency when measuring data with an accelerometer. The accelerometer was positioned on the spinous process of vertebra L3 of a participant and sampled accelerations at 148.1Hz on its X, Y and Z axes during a trial of the SUAO test. The net acceleration was then calculated from the X, Y and Z components to create the accelerometer signal for the Fast Fourier Transform. Raw values obtained from the transform were then squared to calculate the signal power of the net acceleration across a frequency spectrum. In the SUAO test's frequency spectrum, the majority of the signal's power occurred at less than 2 Hz (Figure B-1). This result suggests that the Nyquist frequency of the accelerometer for the SUAO test is 4 Hz, which is also the minimum acceptable sampling frequency.
Figure B-1. Accelerometer's power across a frequency spectrum when measuring net acceleration from the SUAO test.
Appendix C: SUAO Test’s Required Number of Trials

Multiple trials were taken to ensure that the SUAO test's measures were accurate, and the minimum number of these required was determined. A low number of trials is optimal to keep the SUAO test time-efficient. To discover the required number, 17 participants completed ten trials of the SUAO test. The standard deviations of the test's lift acceleration, impact acceleration, and movement time were compared based on the number of trials used to compute each measure's mean value.

The individual and group standard deviations are all displayed in Figures C-1, C-2 and C-3, and were used to decide on the required number of trials. To interpret the results, the standard deviations for each measure were looked at as a group to see if there were inflection points in the curves. Although there were individual outlying values, the inflection point of the group curve occurred at three trials for movement time and five trials for lift and impact acceleration. After these inflection points, the standard deviations were stable with an increasing number of trials. Therefore, all measures of the SUAO test can be gathered accurately when a minimum of five trials are performed.
Figure C-1. Standard deviation of lift acceleration, calculated from the mean found for different numbers of trials. Standard deviations are reported for each participant (thin lines), and the grand mean was calculated for the group (thick line).
Figure C-2. Standard deviation of the impact acceleration, calculated from the mean found for different numbers of trials. Standard deviations are reported for each participant (thin lines), and the grand mean was calculated for the group (thick line).
Figure C-3. Standard deviation of the movement time, calculated from the mean found for different numbers of trials. Standard deviations are reported for each participant (thin lines), and the grand mean was calculated for the group (thick line).
Appendix D: SUAO Test’s Preferred Accelerometer Signal

Extracting the SUAO test variables from the accelerometer's net acceleration is the better of two possible options. The other option is to extract the variables from the accelerometer's vertical acceleration. In both cases, the SUAO test variables measured from an accelerometer match closely to the same variables measured from a single axis of the force plate (Figures D-1 and D-2). It may be more intuitive to convert peak vertical accelerations to lift and impact indexes, since lift and impact index from the force plate are derived from one axis of ground reaction force, but extracting measures from net acceleration eliminates accelerometer positioning errors, simplifying its positioning.
Figure D-1. Body weight index derived from the vertical acceleration of the accelerometer (grey line) and the vertical force of the force plate (black line). The body weight index from the accelerometer was calculated by converting $m/s^2$ to $g$, subtracting 1 $g$, then multiplying by 100, and the body weight index from the force plate was calculated by subtracting the individual's body weight from the recorded force, then dividing by body weight and multiplying by 100. Also displayed are the weight shift (WS), lift index (L) and impact index (I).
Figure D-2. Body weight index derived from the net acceleration of the accelerometer (grey line) and the vertical force of the force plate (black line). The body weight index from the accelerometer was calculated by converting $m/s^2$ to $g$, subtracting 1 $g$, then multiplying by 100, and the body weight index from the force plate was calculated by subtracting the individual's body weight from the recorded force, then dividing by body weight and multiplying by 100. Also displayed are the weight shift (WS), lift index (L) and impact index (I).
Appendix E: Bland-Altman Plots

To further assess the level of agreement between the force plate and accelerometer on the SUAO test, Bland-Altman plots were created for the Lift Index, Impact Index and Movement Time scores (Figures E-1 – E-3). Because the mean difference between the devices, across all participants, was statistically different from 0 for Lift Index and Impact Index (one sample t-tests, $P_s < 0.05$), the devices were not in complete agreement.

Figure E-1. Comparison of the force plate and accelerometer’s mean Lift Index and devices’ difference in Lift Index. The difference was calculated as the accelerometer score subtracted from the force plate score. The middle horizontal line represents the mean across all devices and participants and the top and bottom lines are the upper and lower 95% confidence intervals.
Figure E-2. Comparison of the force plate and accelerometer's mean Impact Index and devices’ difference in Impact Index. The difference was calculated as the accelerometer score subtracted from the force plate score. The middle horizontal line represents the mean across all devices and participants and the top and bottom lines are the upper and lower 95% confidence intervals.
Figure E-3. Comparison of the force plate and accelerometer's mean Movement Time and devices’ difference in Movement Time. The difference was calculated as the accelerometer score subtracted from the force plate score. The middle horizontal line represents the mean across all devices and participants and the top and bottom lines are the upper and lower 95% confidence intervals.
Appendix F: SUAO Test’s Optimal Accelerometer Position

Although several accelerometer positions were considered, only two were tested: the lower back and the foot of the trail leg (it lifts off the force plate during the lift phase and strikes the force plate at touchdown). Since an accelerometer should be positioned as close to the force plate-contact point as possible to eliminate timing delays as the force is transmitted to the more distal segments, the foot of the trail leg was selected as a possible position. The lower back at the level of the L3 vertebra was selected as it is close to the body’s center of mass.

The relationship between the acceleration profiles of the foot and low back accelerometers with the force plate can be seen in Figures F-1 and F-2. The foot accelerometer measured the impact index accurately but not the lift index or movement time. From the foot acceleration profile the weight shift and lift index event locations are unclear. Meanwhile, all events recorded by the vertebra L3 accelerometer closely resemble the force plate's, indicating that it is the better accelerometer position for the SUAO test.
Figure F-1. Foot accelerometer (grey line) and force plate (black line) measured body weight index for the SUAO test. The body weight index from the accelerometer was calculated by converting $m/s^2$ to $g$, subtracting 1 g, then multiplying by 100, and the body weight index from the force plate was calculated by subtracting the individual's body weight from the recorded force, then dividing by body weight and multiplying by 100. Also displayed are the Weight Shift (WS), Lift Index (L) and Impact Index (I).
Figure F-2. Vertebra L3 accelerometer (grey line) and force plate (black line) measured body weight index for the SUAO test. The body weight index from the accelerometer was calculated by converting $m/s^2$ to $g$, subtracting $1\, g$, then multiplying by 100, and the body weight index from the force plate was calculated by subtracting the individual's body weight from the recorded force, then dividing by body weight and multiplying by 100. Also displayed are the Weight Shift (WS), Lift Index (L) and Impact Index (I).
## Appendix G: Tegner Activity-Level Scale

**TEGNER ACTIVITY LEVEL SCALE**

Please indicate in the spaces below the HIGHEST level of activity that you participated in **BEFORE YOUR INJURY** and the highest level you are able to participate in **CURRENTLY**.

**BEFORE INJURY:** Level________  **CURRENT:** Level________

<table>
<thead>
<tr>
<th>Level</th>
<th>Activity Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 10</td>
<td>Competitive sports- soccer, football, rugby (national elite)</td>
</tr>
<tr>
<td>Level 9</td>
<td>Competitive sports- soccer, football, rugby (lower divisions), ice hockey, wrestling, gymnastics, basketball</td>
</tr>
<tr>
<td>Level 8</td>
<td>Competitive sports- racquetball or bandy, squash or badminton, track and field athletics (jumping, etc.), down-hill skiing</td>
</tr>
<tr>
<td>Level 7</td>
<td>Competitive sports- tennis, running, motocars speedway, handball</td>
</tr>
<tr>
<td></td>
<td>Recreational sports- soccer, football, rugby, bandy, ice hockey, basketball, squash, racquetball, running</td>
</tr>
<tr>
<td>Level 6</td>
<td>Recreational sports- tennis and badminton, handball, racquetball, down-hill skiing, jogging at least 5 times per week</td>
</tr>
<tr>
<td>Level 5</td>
<td>Work- heavy labor (construction, etc.)</td>
</tr>
<tr>
<td></td>
<td>Competitive sports- cycling, cross-country skiing,</td>
</tr>
<tr>
<td></td>
<td>Recreational sports- jogging on uneven ground at least twice weekly</td>
</tr>
<tr>
<td>Level 4</td>
<td>Work- moderately heavy labor (e.g. truck driving, etc.)</td>
</tr>
<tr>
<td>Level 3</td>
<td>Work- light labor (nursing, etc.)</td>
</tr>
<tr>
<td>Level 2</td>
<td>Work- light labor</td>
</tr>
<tr>
<td></td>
<td>Walking on uneven ground possible, but impossible to back pack or hike</td>
</tr>
<tr>
<td>Level 1</td>
<td>Work- sedentary (secretarial, etc.)</td>
</tr>
<tr>
<td>Level 0</td>
<td>Sick leave or disability pension because of knee problems</td>
</tr>
</tbody>
</table>

Appendix H: Sample Size Calculation for Manuscript B

The required sample size for the control and ACLR groups was calculated using G*Power V3.1.9.2 (Faul, Erdfelder, Lang, & Buchner, 2007) (Figure H-1). The primary analysis was a comparison of two independent means. For this test, the effect size was set as large (Cohen’s $d = 0.8$), the alpha error probability as 0.05, and the power as 0.80. Using these parameters, the required sample sizes for the control and ACLR groups were 26 each.
Figure H-1. Output of G*Power sample size calculation.
Appendix I: Letter of Information and Ethics Consent Forms

Development of Clinical Tests for the Objective Measurement of Lower Limb Function

Dear Participant,

This letter is an invitation to participate in a research study that has the goal of developing new tests to measure how the lower limb performs after an injury to the knee ligaments or surgery to repair injured ligaments. This information will improve rehabilitation training following a sports injury or after joint surgery.

Before you decide whether or not to take part in the study you should read this information. It is very important that you read and understand the following information. This form explains the study, including the risks and benefits of taking part in the study. You will be given this information sheet to keep. Please feel free to ask the study investigator(s) or research staff any questions that will help you understand the study and what you are expected to do. Please ask if there is anything that is not clear to you or if you would like more information before deciding whether or not to take part in the study.

The study has been reviewed for ethical compliance by the Queen’s University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board. This group is responsible for safeguarding the safety, rights and well-being of human subjects participating in clinical trials. The trial will be conducted in keeping with international quality standards which have been adopted by Health Canada.

**Purpose of the Study**

The main objective of our study is to quantify the knee’s performance, which includes its motion, the forces it experiences and the control you have over the knee’s function. This is of importance in both sports medicine and rehabilitative medicine.

The specific aims of the study are:
To determine which measures distinguish between healthy participants who have never had a lower limb injury and those who have had their ACL surgically repaired and have been cleared to return to their full, active lifestyle. These participants are also considered healthy in that they have no visible disability as a consequence of their injury or surgery.

To determine if these measures can distinguish between ACL patients at different times during rehabilitation.

From these measures, to develop simple, reliable versions that can be used quickly and effectively in the clinic as an adjunct to the clinician’s current evaluation protocol.

You are being asked to participate in this research study either because you have healthy, normal knees, have had your ACL repaired and are no longer undergoing rehabilitation, are currently undergoing rehabilitation after having a torn ACL surgically repaired, or you have been diagnosed with a complete or partial rupture of the anterior cruciate ligament (ACL).

**Voluntary Participation and Withdrawal**

Your participation in this study is voluntary and you will be given adequate time to decide whether you wish to participate in this study. You may decline to participate or are free to withdraw from the trial at any time without reason, without penalty or loss of benefits to which you are otherwise entitled. Your decision to decline to participate or withdraw will not affect the standard of care you receive or your relationship with your investigator(s). If you do not wish to participate or if you withdraw from the trial, neither your current nor future medical care will be adversely affected.

If you agree to participate in the trial, the investigator(s)/study coordinator(s) will ensure, with your agreement, that your family doctor is informed about your participation. The investigator(s) may also remove you from the study at any time without your consent for reasons that include: your failure to follow study requirements; the occurrence of unusual or serious side effects; anytime the investigator(s) thinks it is in your best interest; or if the study has ended. If this were to happen, you would be informed of the reason(s). You will be informed promptly of any important findings that are found from your participation.

**Benefit from Participating in this Study**

All tests and examinations required as part of this study will be provided at no cost. Moreover, other individuals suffering from an ACL injury may benefit from the overall conclusion to be drawn from the results of this study.

**Study Procedures**

*Before starting:* Please bring with you a tank top or sleeveless shirt and shorts to wear for testing. If you have not completed the online questionnaires before arrival, you will be asked to complete them before testing can begin. This time will be on top of the total time of this study. *(10 minutes)*
**Anthropometry:** The research team will collect some physical measurements that will be used later for data analysis. These measurements will include: height, weight, and leg lengths. (5 minutes)

**Warm-up:** You will be asked to perform 3 minutes of general warm-up on a cycle ergometer with a low resistance setting. This will be followed by a session of guided lower body stretching. (5 minutes)

**Testing:** You will fill out the questionnaires and be asked to perform the following listed exercises. You will be given a minimum of 2 minutes of rest between exercises, and rest between exercise repetitions to avoid fatigue.

1. **Psychological Questionnaires** – Depending on your health status you will fill out several subjective questionnaires. They include the PAR-Q, International Knee Documentation Committee Questionnaire, Tampa Scale for Kinesiophobia, and the Tegner Activity Scale. These questionnaires gauge your general health, your level of pain, your opinion about your knee’s function and how your injury has affected your daily life.

2. **Isokinetic Strength Testing** - You will sit comfortably in the dynamometer chair, with your pelvis, shoulders, and legs stabilization with straps. Once strapped in, the dynamometer’s lever arm will be aligned with the knee joint’s axis of rotation. You will then complete warm-up repetitions of increasing sub-maximal concentric and eccentric contractions. Rest will be given as needed. After adequate rest, you will perform up to three repetitions at what you believe is your maximal strength. During testing of injured knees, you will be reminded to only exert as much force as you are comfortable with. Testing will be performed for concentric contractions with a maximum of 60° range of motion (ROM). The testing velocities is 60°/s.

3. **Single Leg Horizontal Hop** – You will stand on one leg and then jump forward as far as possible, landing on both feet.

4. **Step Up and Over** – You will stand in front of box. With your lead leg you will step up onto the box. Your trail leg will rise up and over the box to step down on a force plate positioned on the other side of the box. You will then step down from the box.

5. **Drop Vertical Jump** – You will stand on top of a box and then drop onto a force plate and, as quickly as possible, jump as high as they can.

6. **Unilateral Balance** - You will balance on one leg on a flat surface with your eyes open. You will try to balance for as long as you can to a maximum of 30 seconds. The timing will stop as soon as you lose your balance or your non-balance foot touches the floor.

7. **Forward lunge** – You will start from a standing position and move to a distance corresponding to your individual leg length. You will step forward with one foot flexing that knee to approximately 90°-100°, while your contra-lateral knee comes close to the floor without touching. After reaching this position, you will return to your starting position.
You will be asked to perform up to 3 practice repetitions of each exercise to familiarize yourself with the exercise. All movement conditions will be performed with only the upper body mass (above the knee) acting as external resistance (e.g. weights will NOT be used).

Rest will be given between each test repetition (typically 10-30 seconds for low-exertion tests and at least 30 seconds for high-exertion tests) and between experimental protocols (typically 2 minutes). During trial performance, if you indicate an RPE score that is 2 scores above that of your initial trial, additional rest will be given until you report full recovery (your score returns to its initial baseline). The total time for testing, including the warm-up and exercises, will be no more than 1.5 hours.

**Risks and Benefits of Participation:**

To the best of our knowledge, there are no added risks to participating in this study. The largest risk would be for people who have medical contraindications, such as cardiovascular problems, or musculoskeletal injuries. To accommodate these risks, you will be asked to fill out the Physical Activity Readiness questionnaire (PAR-Q). Answering yes to any of the questions will exclude you from testing unless you are clear by your doctor to perform any of the listed activities. Another possible risk is that of a pulled muscle. While this will be minimized by performing a warm-up, practice trails and by monitoring fatigue, a pulled muscle signals the end of testing for that day. A mild pulled muscle is treated with rest and if pain or stiffness continue you may want to seek medical advice. If you wish, another day will be scheduled to complete the testing.

In terms of benefits from this study, there are no direct personal benefits expected. However, your participation will contribute to improvements in the design of exercise programs for rehabilitation training following a sports injury or after joint surgery.

**Confidentiality**

All information obtained during the course of this study is strictly confidential and your identity will be protected to the extent possible in all data analyses and publications. Your data will be assigned a code number for your file. All data will be recorded and protected by passwords in computer files with only the principal researcher and research assistants granted access. Only summary data will be used so that no individual can be identified. We wish to take some photos of the study but only require permission from one or two participants. These photos will most likely include only the appendages tested to show the set-up, if the face is in any of the photographs, it will be blurred out.

**Voluntary Participation and Withdrawal from the Study:**

As a participant, you are a volunteer and may withdraw from the study at any time without coercion or penalty. You may withdraw after hearing about the details of the study or withdraw at any point during the study with no penalty. By signing this consent form, you do not waive your legal rights nor release the investigators and sponsors from their legal and professional responsibilities.

**Contacts:**
Patrick Costigan, Ph.D. Associate Professor, School of Kinesiology and Health Studies, Queen’s University (613) 533-6000 x79037
Dr. Davide Bardana, Orthopedic Surgeon, Department of Orthopedic Surgery, Kingston General Hospital (613) 549-6666 x 6333
Dr. John Rudan Head of the Department of Surgery, Kingston General Hospital (613) 549-6666 x 3671
Jean Côté, Ph.D. Director, School of Kinesiology and Health Studies, Queen’s University (613) 533-6000 x 33054

This study has been granted clearance according to the recommended principles of Canadian ethics guidelines, and Queen’s policies. Any questions about study participation may be directed to the Dr. Patrick Costigan by phone at 613-533-6000 ext: 79037 or email at pat.costigan@queensu.ca. Any ethical concerns about the study may be directed to the Chair of the General Research Ethics Board at chair.GREB@queensu.ca or 613-555-6081.
What does my signature mean?

By signing below, I am indicating that:

- I have read and understood this Consent Form and I have had any questions answered to my satisfaction
- I understand my participation in the study.
- I realize that my participation is voluntary and that I can withdraw at any time without penalty or coercion
- I was given a copy of the Information and Ethics Consent Letter to read and keep
- I realize that my personal data will be kept confidential.
- I can contact any of people in this letter if I have questions, concerns or complaints
- By signing this consent form I do not waive my legal rights nor release the investigator(s) and sponsors from their legal and professional responsibilities.

____________________________________
Print your Name

________________________
Date

____________________________________
Signature of Participant

____________________________________
Signature of Witness

We would like to ask at least one or two individuals to permit photos to be taken of the tasks. Please initial here if you are willing to permit photos to be taken ____________.
Witness Initials: ________________

Thank you.
Patrick Costigan, Ph.D., School of Kinesiology and Health Studies, Queen’s University
Principal Investigator
Ethics Consent: Participant’s Copy

Development of Clinical Tests for the Objective Measurement of Lower Limb Function

This page is for the researchers to verify that you are willing to participate in the above study. By signing this page, you are declaring the following:

- You were given a verbal presentation about the above-mentioned research study
- You were given a copy of the Information and Ethics Consent Letter to read and keep
- You realize you can withdraw at any time without penalty or coercion
- You can contact any of people in this letter if you have questions, concerns or complaints
- You realize that your data will be kept confidential.
- By signing this consent form you do not wave your legal rights nor release the investigator(s) and sponsors from their legal and professional responsibilities.

(Please sign and keep this page for your own records)

____________________________________  __________________
Print your Name                                             Date

____________________________________
Signature of Participant

____________________________________  __________________
Research Assistant                                             Date

Contacts:

Patrick Costigan, Ph.D. Associate Professor, School of Kinesiology and Health Studies, Queen’s University (613) 533-6000 x79037
Dr. Davide Bardana, Orthopedic Surgeon, Department of Orthopedic Surgery, Kingston General Hospital (613) 549-6666 x 6333
Dr. John Rudan Head of the Department of Surgery, Kingston General Hospital (613) 549-6666 x 3671
Jean Côté, Ph.D. Director, School of Kinesiology and Health Studies, Queen’s University (613) 533-6000 x 33054

This study has been granted clearance according to the recommended principles of Canadian ethics guidelines, and Queen’s policies. Any questions about study participation may be directed to the Dr. Patrick Costigan by phone at 613-533-6000 ext: 79037 or email at pat.costigan@queensu.ca. Any ethical concerns about the study may be directed to the Chair of the General Research Ethics Board at chair.GREB@queensu.ca or 613-555-6081.
Development of Clinical Tests for the Objective
Measurement of Lower Limb Function

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(Please sign and return this page ONLY to the researchers)

__________________________________________  __________________
Print your Name  Date

__________________________________________
Signature of Participant

__________________________________________  __________________
Research Assistant  Date
Appendix J: International Knee Documentation Committee Subjective Knee Form

2000 IKDC SUBJECTIVE KNEE EVALUATION FORM

Your Full Name ____________________________________________

Today's Date: __________ / __________ / __________

Date of Injury: __________ / __________ / __________

SYMPTOMS*:
*Grade symptoms at the highest activity level at which you think you could function without significant symptoms, even if you are not actually performing activities at this level.

1. What is the highest level of activity that you can perform without significant knee pain?

- Very strenuous activities like jumping or pivoting as in basketball or soccer
- Strenuous activities like heavy physical work, skiing or tennis
- Moderate activities like moderate physical work, running or jogging
- Light activities like walking, housework or yard work
- Unable to perform any of the above activities due to knee pain

2. During the past 4 weeks, or since your injury, how often have you had pain?

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Never</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Constant</td>
</tr>
</tbody>
</table>

3. If you have pain, how severe is it?

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>No pain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Worst pain imaginable</td>
</tr>
</tbody>
</table>

4. During the past 4 weeks, or since your injury, how stiff or swollen was your knee?

- Not at all
- Mildly
- Moderately
- Very
- Extremely

5. What is the highest level of activity you can perform without significant swelling in your knee?

- Very strenuous activities like jumping or pivoting as in basketball or soccer
- Strenuous activities like heavy physical work, skiing or tennis
- Moderate activities like moderate physical work, running or jogging
- Light activities like walking, housework, or yard work
- Unable to perform any of the above activities due to knee swelling

6. During the past 4 weeks, or since your injury, did your knee lock or catch?

- Yes
- No

7. What is the highest level of activity you can perform without significant giving way in your knee?

- Very strenuous activities like jumping or pivoting as in basketball or soccer
- Strenuous activities like heavy physical work, skiing or tennis
- Moderate activities like moderate physical work, running or jogging
- Light activities like walking, housework or yard work
- Unable to perform any of the above activities due to giving way of the knee
SPORTS ACTIVITIES:

8. What is the highest level of activity you can participate in on a regular basis?
   - □ Very strenuous activities like jumping or pivoting as in basketball or soccer
   - □ Strenuous activities like heavy physical work, skiing or tennis
   - □ Moderate activities like moderate physical work, running or jogging
   - □ Light activities like walking, housework or yard work
   - □ Unable to perform any of the above activities due to knee

9. How does your knee affect your ability to:

<table>
<thead>
<tr>
<th></th>
<th>Not difficult at all</th>
<th>Minimally difficult</th>
<th>Moderately Difficult</th>
<th>Extremely difficult</th>
<th>Unable to do</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Go up stairs</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>b. Go down stairs</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>c. Kneel on the front of your knee</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>d. Squat</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>e. Sit with your knee bent</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>f. Rise from a chair</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>g. Run straight ahead</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>h. Jump and land on your involved leg</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>i. Stop and start quickly</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>

FUNCTION:

10. How would you rate the function of your knee on a scale of 0 to 10 with 10 being normal, excellent function and 0 being the inability to perform any of your usual daily activities which may include sports?

FUNCTION PRIOR TO YOUR KNEE INJURY:

<table>
<thead>
<tr>
<th>Cannot perform daily activities</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 No limitation in daily activities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td></td>
</tr>
</tbody>
</table>

CURRENT FUNCTION OF YOUR KNEE:

<table>
<thead>
<tr>
<th>Cannot perform daily activities</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 No limitation in daily activities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td></td>
</tr>
</tbody>
</table>
Scoring Instructions for the 2000 IKDC Subjective Knee Evaluation Form

Several methods of scoring the IKDC Subjective Knee Evaluation Form were investigated. The results indicated that summing the scores for each item performed as well as more sophisticated scoring methods.

The responses to each item are scored using an ordinal method such that a score of 1 is given to responses that represent the lowest level of function or highest level of symptoms. For example, item 1, which is related to the highest level of activity without significant pain is scored by assigning a score of 1 to the response “Unable to Perform Any of the Above Activities Due to Knee” and a score of 5 to the response “Very strenuous activities like jumping or pivoting as in basketball or soccer”. For item 2, which is related to the frequency of pain over the past 4 weeks, the response “Constant” is assigned a score of 1 and “Never” is assigned a score of 11.

The IKDC Subjective Knee Evaluation Form is scored by summing the scores for the individual items and then transforming the score to a scale that ranges from 0 to 100. **Note:** The response to item 10 “Function Prior to Knee Injury” is not included in the overall score. The steps to score the IKDC Subjective Knee Evaluation Form are as follows:

1. Assign a score to the individual’s response for each item, such that lowest score represents the lowest level of function or highest level of symptoms.
2. Calculate the raw score by summing the responses to all items with the exception of the response to item 10 “Function Prior to Your Knee Injury”
3. Transform the raw score to a 0 to 100 scale as follows:

$$\text{IKDC Score} = \left[ \frac{\text{Raw Score} - \text{Lowest Possible Score}}{\text{Range of Scores}} \right] \times 100$$

Where the lowest possible score is 18 and the range of possible scores is 87. Thus, if the sum of scores for the 18 items is 60, the IKDC Score would be calculated as follows:

$$\text{IKDC Score} = \left[ \frac{60 - 18}{87} \right] \times 100$$

$$\text{IKDC Score} = 48.3$$

The transformed score is interpreted as a measure of function such that higher scores represent higher levels of function and lower levels of symptoms. A score of 100 is interpreted to mean no limitation with activities of daily living or sports activities and the absence of symptoms.

The IKDC Subjective Knee Score can still be calculated if there are missing data, as long as there are responses to at least 90% of the items (i.e., responses have been provided for at least 16 items). To calculate the raw IKDC score when there are missing data, substitute the average score of the items that have been answered for the missing item score(s). Once the raw IKDC score has been calculated, it is transformed to the IKDC Subjective Knee Score as described above.
**Appendix K: Modified Tampa Scale for Kinesiophobia (TSK-11)**

Modified Tampa Scale for Kinesiophobia  
(Woby et al., 2005)

1 = strongly disagree  
2 = disagree  
3 = agree  
4 = strongly agree

<table>
<thead>
<tr>
<th></th>
<th>Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I'm afraid that I might injure myself if I exercise</td>
</tr>
<tr>
<td>2</td>
<td>If I were to overcome it, my pain would increase</td>
</tr>
<tr>
<td>3</td>
<td>My body is telling me I have something dangerously wrong</td>
</tr>
<tr>
<td>4</td>
<td>People aren't taking my medical condition seriously enough</td>
</tr>
<tr>
<td>5</td>
<td>My accident has put my body at risk for the rest of my life</td>
</tr>
<tr>
<td>6</td>
<td>Pain always means I have injured my body</td>
</tr>
<tr>
<td>7</td>
<td>Simply being careful that I do not make any unnecessary movements is the safest thing I can do to prevent my pain from worsening</td>
</tr>
<tr>
<td>8</td>
<td>I wouldn't have this much pain if there wasn't something potentially dangerous going on in my body</td>
</tr>
<tr>
<td>9</td>
<td>Pain lets me know when to stop exercising so that I don't injure myself</td>
</tr>
<tr>
<td>10</td>
<td>I can't do all the things normal people do because it's too easy for me to get injured</td>
</tr>
<tr>
<td>11</td>
<td>No one should have to exercise when he/she is in pain</td>
</tr>
</tbody>
</table>

Appendix L: Non-Normal Distribution of the ACLR group’s Lift Symmetry and Impact Symmetry

From the Shapiro-Wilk normality tests, the ACLR group was not normally distributed for either Lift Symmetry (Statistic = .88, df = 20, \( P = .016 \)) (Figure L-1) nor Impact Symmetry (Statistic = .84, df = 20, \( P = .003 \)) (Figure L-2).

![Histogram of Lift Symmetry](image)

Figure L-1. Frequency distribution of the ACLR group’s Lift Symmetry.
Figure L-2. Frequency distribution of the ACLR group’s Impact Symmetry.
Appendix M: Individual ACLR Patient SUAO Test Performance

To assess control and ACLR patient performance in Chapter 5 individually, different cases were created based on scores for Lift Index, Impact Index and Movement Time. To create these cases, the control leg’s median and standard deviation for each variable were used (Table M-1). A 2 SD range (1 SD above and below the median) was used to classify “normal” performance for each variable. Involved and uninvolved leg performances within and outside of this range were then used to classify ACLR patients (Tables M-2 - M-4), and the number of patients that fit each case were totaled (Table M-5). For controls, non-dominant and dominant leg performances within and outside of the “normal” range were used (Tables M-6 – M-8), then totaled (Table M-9).

Table M-1. Control leg medians, SDs, and lower (Median – 1 SD) and upper (Median + 1 SD) boundaries of the “normal” range for Lift Index, Impact Index and Movement Time.

<table>
<thead>
<tr>
<th>SUAO Test Measure</th>
<th>Median</th>
<th>SD</th>
<th>Lower Boundary</th>
<th>Upper Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift Index</td>
<td>75.2</td>
<td>23.3</td>
<td>51.9</td>
<td>98.5</td>
</tr>
<tr>
<td>Impact Index</td>
<td>121.7</td>
<td>28.1</td>
<td>93.6</td>
<td>149.8</td>
</tr>
<tr>
<td>Movement Time (s)</td>
<td>2.15</td>
<td>0.25</td>
<td>1.90</td>
<td>2.40</td>
</tr>
</tbody>
</table>
Table M-2. Case classification of ACLR patients for Lift Index. Cases are named for whether they were within the control leg’s range on both legs (Normal), higher than the control leg’s range (High), or lower than the control leg’s range (Low) for the involved, uninvolved, or both legs. Up and down arrows indicate values that are higher than the upper boundary and lower than the lower boundary, respectively.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Uninvolved Leg</th>
<th>Involved Leg</th>
<th>Case</th>
<th>Limb Symmetry Index</th>
<th>Time Since Surgery (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>62.2</td>
<td>63.7</td>
<td>Normal</td>
<td>102.5</td>
<td>9.2</td>
</tr>
<tr>
<td>K</td>
<td>69.5</td>
<td>75.4</td>
<td>Normal</td>
<td>108.5</td>
<td>5.6</td>
</tr>
<tr>
<td>C</td>
<td>78.8</td>
<td>92.4</td>
<td>Normal</td>
<td>117.2</td>
<td>7.8</td>
</tr>
<tr>
<td>E</td>
<td>65.3</td>
<td>78.0</td>
<td>Normal</td>
<td>119.3</td>
<td>1.7</td>
</tr>
<tr>
<td>I</td>
<td>54.3</td>
<td>67.2</td>
<td>Normal</td>
<td>123.6</td>
<td>5.9</td>
</tr>
<tr>
<td>Q</td>
<td>64.4</td>
<td>81.5</td>
<td>Normal</td>
<td>126.6</td>
<td>5.9</td>
</tr>
<tr>
<td>Y</td>
<td>67.6</td>
<td>93.2</td>
<td>Normal</td>
<td>137.9</td>
<td>2.8</td>
</tr>
<tr>
<td>D</td>
<td>57.5</td>
<td>79.7</td>
<td>Normal</td>
<td>138.7</td>
<td>1.6</td>
</tr>
<tr>
<td>T</td>
<td>43.4</td>
<td>65.6</td>
<td>Normal</td>
<td>151.2</td>
<td>4.7</td>
</tr>
<tr>
<td>J</td>
<td>43.1 ↓</td>
<td>53.3</td>
<td>Low Uninvolved</td>
<td>123.6</td>
<td>6.1</td>
</tr>
<tr>
<td>O</td>
<td>47.8 ↓</td>
<td>72.4</td>
<td>Low Uninvolved</td>
<td>151.4</td>
<td>3.3</td>
</tr>
<tr>
<td>M</td>
<td>40.5 ↓</td>
<td>66.8</td>
<td>Low Uninvolved</td>
<td>165.0</td>
<td>1.3</td>
</tr>
<tr>
<td>P</td>
<td>44.2 ↓</td>
<td>84.0</td>
<td>Low Uninvolved</td>
<td>189.9</td>
<td>1.7</td>
</tr>
<tr>
<td>N</td>
<td>43.6 ↓</td>
<td>94.4</td>
<td>Low Uninvolved</td>
<td>216.4</td>
<td>2.9</td>
</tr>
<tr>
<td>A</td>
<td>38.5 ↓</td>
<td>30.9 ↓</td>
<td>Low Both</td>
<td>80.2</td>
<td>8.8</td>
</tr>
<tr>
<td>R</td>
<td>38.5 ↓</td>
<td>45.8 ↓</td>
<td>Low Both</td>
<td>118.8</td>
<td>6.9</td>
</tr>
<tr>
<td>H</td>
<td>39.4 ↓</td>
<td>50.9 ↓</td>
<td>Low Both</td>
<td>128.9</td>
<td>2.9</td>
</tr>
<tr>
<td>U</td>
<td>95.2</td>
<td>117.5 ↑</td>
<td>High Involved</td>
<td>123.4</td>
<td>8.3</td>
</tr>
<tr>
<td>L</td>
<td>79.5</td>
<td>102.7 ↑</td>
<td>High Involved</td>
<td>129.1</td>
<td>1.9</td>
</tr>
<tr>
<td>V</td>
<td>85.4</td>
<td>117.0 ↑</td>
<td>High Involved</td>
<td>137.0</td>
<td>5.8</td>
</tr>
<tr>
<td>G</td>
<td>78.0</td>
<td>126.0 ↑</td>
<td>High Involved</td>
<td>161.6</td>
<td>3.5</td>
</tr>
<tr>
<td>B</td>
<td>63.5</td>
<td>108.7 ↑</td>
<td>High Involved</td>
<td>171.1</td>
<td>8.8</td>
</tr>
<tr>
<td>X</td>
<td>101.7 ↑</td>
<td>107.5 ↑</td>
<td>High Both</td>
<td>105.7</td>
<td>7.9</td>
</tr>
<tr>
<td>S</td>
<td>110.4 ↑</td>
<td>150.1 ↑</td>
<td>High Both</td>
<td>135.9</td>
<td>5.8</td>
</tr>
<tr>
<td>F</td>
<td>38.1 ↓</td>
<td>106.4 ↑</td>
<td>Low Uninvolved, High Involved</td>
<td>279.1</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Table M-3. Case classification of ACLR patients for Impact Index. Cases are named for whether they were within the control leg’s range on both legs (Normal), higher than the control leg’s range (High), or lower than the control leg’s range (Low) for the involved, uninvolved, or both legs. Up and down arrows indicate values that are higher than the upper boundary and lower than the lower boundary, respectively.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Uninvolved Leg</th>
<th>Involved Leg</th>
<th>Case</th>
<th>Limb Symmetry Index</th>
<th>Time Since Surgery (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>119.2</td>
<td>111.4</td>
<td>Normal</td>
<td>93.5</td>
<td>1.6</td>
</tr>
<tr>
<td>S</td>
<td>143.1</td>
<td>148.4</td>
<td>Normal</td>
<td>103.7</td>
<td>5.8</td>
</tr>
<tr>
<td>R</td>
<td>118.6</td>
<td>123.6</td>
<td>Normal</td>
<td>104.3</td>
<td>6.9</td>
</tr>
<tr>
<td>C</td>
<td>95.4</td>
<td>100.9</td>
<td>Normal</td>
<td>105.8</td>
<td>7.8</td>
</tr>
<tr>
<td>Y</td>
<td>118.3</td>
<td>131.7</td>
<td>Normal</td>
<td>111.3</td>
<td>2.8</td>
</tr>
<tr>
<td>Q</td>
<td>108.1</td>
<td>121.9</td>
<td>Normal</td>
<td>112.8</td>
<td>5.9</td>
</tr>
<tr>
<td>T</td>
<td>100.4</td>
<td>118.9</td>
<td>Normal</td>
<td>118.4</td>
<td>4.7</td>
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<td>139.1</td>
<td>Normal</td>
<td>121.8</td>
<td>8.3</td>
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<tr>
<td>E</td>
<td>104.1</td>
<td>131.5</td>
<td>Normal</td>
<td>126.3</td>
<td>1.7</td>
</tr>
<tr>
<td>N</td>
<td>108.5</td>
<td>149.7</td>
<td>Normal</td>
<td>138.1</td>
<td>2.9</td>
</tr>
<tr>
<td>M</td>
<td>100.8</td>
<td>144.5</td>
<td>Normal</td>
<td>143.4</td>
<td>1.3</td>
</tr>
<tr>
<td>O</td>
<td>84.8 ↓</td>
<td>93.6</td>
<td>Low Uninvolved</td>
<td>110.3</td>
<td>3.3</td>
</tr>
<tr>
<td>H</td>
<td>76.8 ↓</td>
<td>111.8</td>
<td>Low Uninvolved</td>
<td>145.7</td>
<td>2.9</td>
</tr>
<tr>
<td>J</td>
<td>65.3 ↓</td>
<td>116.6</td>
<td>Low Uninvolved</td>
<td>178.5</td>
<td>6.1</td>
</tr>
<tr>
<td>F</td>
<td>62.4 ↓</td>
<td>119.7</td>
<td>Low Uninvolved</td>
<td>191.8</td>
<td>2.3</td>
</tr>
<tr>
<td>A</td>
<td>90.5 ↓</td>
<td>87.5 ↓</td>
<td>Low Both</td>
<td>96.6</td>
<td>8.8</td>
</tr>
<tr>
<td>I</td>
<td>104.4</td>
<td>153.0 ↑</td>
<td>High Involved</td>
<td>146.6</td>
<td>5.9</td>
</tr>
<tr>
<td>V</td>
<td>124.9</td>
<td>196.3 ↑</td>
<td>High Involved</td>
<td>157.2</td>
<td>5.8</td>
</tr>
<tr>
<td>X</td>
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<td>178.8 ↑</td>
<td>High Involved</td>
<td>168.8</td>
<td>7.9</td>
</tr>
<tr>
<td>K</td>
<td>93.6</td>
<td>159.5 ↑</td>
<td>High Involved</td>
<td>170.5</td>
<td>5.6</td>
</tr>
<tr>
<td>B</td>
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<td>High Involved</td>
<td>177.6</td>
<td>8.8</td>
</tr>
<tr>
<td>G</td>
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<td>247.3 ↑</td>
<td>High Involved</td>
<td>213.7</td>
<td>3.5</td>
</tr>
<tr>
<td>L</td>
<td>91.3 ↓</td>
<td>173.7 ↑</td>
<td>Low Uninvolved, High Involved</td>
<td>190.2</td>
<td>1.9</td>
</tr>
<tr>
<td>W</td>
<td>92.6 ↓</td>
<td>217.5 ↑</td>
<td>Low Uninvolved, High Involved</td>
<td>235.0</td>
<td>9.2</td>
</tr>
<tr>
<td>P</td>
<td>82.5 ↓</td>
<td>265.5 ↑</td>
<td>Low Uninvolved, High Involved</td>
<td>322.0</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Table M-4. Case classification of ACLR patients for Movement Time. Cases are named for whether they were within the control leg’s range on both legs (Normal), higher than the control leg’s range (High), or lower than the control leg’s range (Low) for the involved, uninvolved, or both legs. Up and down arrows indicate values that are higher than the upper boundary and lower than the lower boundary, respectively.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Uninvolved Leg</th>
<th>Involved Leg</th>
<th>Case Classification</th>
<th>Limb Symmetry Index</th>
<th>Time Since Surgery (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>2.24</td>
<td>2.02</td>
<td>Normal</td>
<td>90.2</td>
<td>8.3</td>
</tr>
<tr>
<td>X</td>
<td>2.33</td>
<td>2.23</td>
<td>Normal</td>
<td>95.7</td>
<td>7.9</td>
</tr>
<tr>
<td>T</td>
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<td>2.37</td>
<td>Normal</td>
<td>99.2</td>
<td>4.7</td>
</tr>
<tr>
<td>E</td>
<td>2.2</td>
<td>2.2</td>
<td>Normal</td>
<td>100.0</td>
<td>1.7</td>
</tr>
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<td>D</td>
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<td>Normal</td>
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<td>1.6</td>
</tr>
<tr>
<td>C</td>
<td>1.85 ↓</td>
<td>1.96</td>
<td>Low Uninvolved</td>
<td>105.9</td>
<td>7.8</td>
</tr>
<tr>
<td>Q</td>
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<td>2.09</td>
<td>Low Uninvolved</td>
<td>110.6</td>
<td>5.9</td>
</tr>
<tr>
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<td>Low Uninvolved</td>
<td>130.4</td>
<td>5.8</td>
</tr>
<tr>
<td>I</td>
<td>2.03</td>
<td>1.77 ↓</td>
<td>Low Involved</td>
<td>87.2</td>
<td>5.9</td>
</tr>
<tr>
<td>Y</td>
<td>1.93</td>
<td>1.86 ↓</td>
<td>Low Involved</td>
<td>96.4</td>
<td>2.8</td>
</tr>
<tr>
<td>V</td>
<td>1.85 ↓</td>
<td>1.82 ↓</td>
<td>Low Both</td>
<td>98.4</td>
<td>5.8</td>
</tr>
<tr>
<td>G</td>
<td>1.78 ↓</td>
<td>1.87 ↓</td>
<td>Low Both</td>
<td>105.1</td>
<td>3.5</td>
</tr>
<tr>
<td>R</td>
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<td>90.6</td>
<td>6.9</td>
</tr>
<tr>
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<td>High Involved</td>
<td>106.9</td>
<td>2.9</td>
</tr>
<tr>
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<td>2.54 ↑</td>
<td>High Involved</td>
<td>108.1</td>
<td>8.8</td>
</tr>
<tr>
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<td>2.53 ↑</td>
<td>High Involved</td>
<td>114.0</td>
<td>9.2</td>
</tr>
<tr>
<td>K</td>
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<td>2.87 ↑</td>
<td>High Both</td>
<td>98.3</td>
<td>5.6</td>
</tr>
<tr>
<td>J</td>
<td>2.52 ↑</td>
<td>2.49 ↑</td>
<td>High Both</td>
<td>98.8</td>
<td>6.1</td>
</tr>
<tr>
<td>L</td>
<td>2.48 ↑</td>
<td>2.46 ↑</td>
<td>High Both</td>
<td>99.2</td>
<td>1.9</td>
</tr>
<tr>
<td>A</td>
<td>2.84 ↑</td>
<td>2.82 ↑</td>
<td>High Both</td>
<td>99.3</td>
<td>8.8</td>
</tr>
<tr>
<td>P</td>
<td>2.73 ↑</td>
<td>2.72 ↑</td>
<td>High Both</td>
<td>99.6</td>
<td>1.7</td>
</tr>
<tr>
<td>M</td>
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<td>2.84 ↑</td>
<td>High Both</td>
<td>101.8</td>
<td>1.3</td>
</tr>
<tr>
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<td>High Both</td>
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<td>3.3</td>
</tr>
<tr>
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<td>2.66 ↑</td>
<td>High Both</td>
<td>105.1</td>
<td>2.3</td>
</tr>
<tr>
<td>H</td>
<td>2.52 ↑</td>
<td>2.77 ↑</td>
<td>High Both</td>
<td>109.9</td>
<td>2.9</td>
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</table>
Table M-5. Total number of ACLR patients in each Lift Index, Impact Index and Movement Time case.

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<tr>
<th>Case Classification</th>
<th>Lift Index</th>
<th>Impact Index</th>
<th>Movement Time</th>
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</thead>
<tbody>
<tr>
<td>Normal</td>
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<td>11</td>
<td>5</td>
</tr>
<tr>
<td>Low Uninvolved</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Low Involved</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Low Both</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>High Uninvolved</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>High Involved</td>
<td>5</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>High Both</td>
<td>2</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>Low Uninvolved, High Involved</td>
<td>1</td>
<td>3</td>
<td>0</td>
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<tr>
<td>High Uninvolved, Low Involved</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>All ACLR Patients</td>
<td>25</td>
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Table M-6. Case classification of controls for Lift Index. Cases are named for whether they were within the control leg’s range on both legs (Normal), higher than the control leg’s range (High), or lower than the control leg’s range (Low) for the non-dominant, dominant, or both legs. Up and down arrows indicate values that are higher than the upper boundary and lower than the lower boundary, respectively.

<table>
<thead>
<tr>
<th>Control</th>
<th>Non-Dominant Leg</th>
<th>Dominant Leg</th>
<th>Case</th>
<th>Limb Symmetry Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>64.1</td>
<td>86.5</td>
<td>Normal</td>
<td>74.1</td>
</tr>
<tr>
<td>Y</td>
<td>57.6</td>
<td>74.1</td>
<td>Normal</td>
<td>77.7</td>
</tr>
<tr>
<td>G</td>
<td>77.2</td>
<td>97.1</td>
<td>Normal</td>
<td>79.4</td>
</tr>
<tr>
<td>E</td>
<td>73.4</td>
<td>85.1</td>
<td>Normal</td>
<td>86.2</td>
</tr>
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<td>Normal</td>
<td>86.9</td>
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<td>75.1</td>
<td>Normal</td>
<td>87.9</td>
</tr>
<tr>
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<td>75.1</td>
<td>80.7</td>
<td>Normal</td>
<td>93.1</td>
</tr>
<tr>
<td>N</td>
<td>75.4</td>
<td>79.7</td>
<td>Normal</td>
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</tr>
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<td>Normal</td>
<td>94.6</td>
</tr>
<tr>
<td>Z</td>
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<td>80.4</td>
<td>Normal</td>
<td>96.6</td>
</tr>
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<td>92.3</td>
<td>94.3</td>
<td>Normal</td>
<td>97.8</td>
</tr>
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<td>K</td>
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<td>85.1</td>
<td>Normal</td>
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</tr>
<tr>
<td>V</td>
<td>60.2</td>
<td>58.2</td>
<td>Normal</td>
<td>103.5</td>
</tr>
<tr>
<td>B</td>
<td>77.1</td>
<td>73.9</td>
<td>Normal</td>
<td>104.3</td>
</tr>
<tr>
<td>X</td>
<td>78.6</td>
<td>72.9</td>
<td>Normal</td>
<td>107.8</td>
</tr>
<tr>
<td>Q</td>
<td>79.8</td>
<td>72.9</td>
<td>Normal</td>
<td>109.5</td>
</tr>
<tr>
<td>J</td>
<td>86.2</td>
<td>75.4</td>
<td>Normal</td>
<td>114.3</td>
</tr>
<tr>
<td>A</td>
<td>84.0</td>
<td>72.4</td>
<td>Normal</td>
<td>116.1</td>
</tr>
<tr>
<td>T</td>
<td>64.0</td>
<td>54.5</td>
<td>Normal</td>
<td>117.4</td>
</tr>
<tr>
<td>D</td>
<td>89.1</td>
<td>71.6</td>
<td>Normal</td>
<td>124.5</td>
</tr>
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<td>W</td>
<td>76.8</td>
<td>54.9</td>
<td>Normal</td>
<td>139.7</td>
</tr>
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<td>47.5</td>
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<td>111.2</td>
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<td>O</td>
<td>55.6</td>
<td>47.9</td>
<td>Low Dominant</td>
<td>116.0</td>
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<td>113.3</td>
<td>High Dominant</td>
<td>64.9</td>
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<td>131.2</td>
<td>High Both</td>
<td>90.4</td>
</tr>
<tr>
<td>H</td>
<td>138.0</td>
<td>147.8</td>
<td>High Both</td>
<td>93.4</td>
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</table>
Table M-7. Case classification of controls for Impact Index. Cases are named for whether they were within the control leg’s range on both legs (Normal), higher than the control leg’s range (High), or lower than the control leg’s range (Low) for the non-dominant, dominant, or both legs. Up and down arrows indicate values that are higher than the upper boundary and lower than the lower boundary, respectively.

<table>
<thead>
<tr>
<th>Control</th>
<th>Non-Dominant Leg</th>
<th>Dominant Leg</th>
<th>Case</th>
<th>Limb Symmetry Index</th>
</tr>
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<td>Normal</td>
<td>91.4</td>
</tr>
<tr>
<td>S</td>
<td>121.8</td>
<td>129.4</td>
<td>Normal</td>
<td>94.2</td>
</tr>
<tr>
<td>P</td>
<td>121.4</td>
<td>125.2</td>
<td>Normal</td>
<td>97.0</td>
</tr>
<tr>
<td>V</td>
<td>108.3</td>
<td>111.3</td>
<td>Normal</td>
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<td>C</td>
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<td>108.8</td>
<td>Normal</td>
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<td>Normal</td>
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<td>Normal</td>
<td>101.2</td>
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<td>Normal</td>
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<td>88.9</td>
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<td>T</td>
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<td>99.9</td>
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<td>I</td>
<td>159.1</td>
<td>166.3</td>
<td>High Both</td>
<td>95.7</td>
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</table>
Table M-8. Case classification of controls for Movement Time. Cases are named for whether they were within the control leg’s range on both legs (Normal), higher than the control leg’s range (High), or lower than the control leg’s range (Low) for the non-dominant, dominant, or both legs. Up and down arrows indicate values that are higher than the upper boundary and lower than the lower boundary, respectively.

<table>
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<tr>
<th>Control</th>
<th>Non-Dominant Leg</th>
<th>Dominant Leg</th>
<th>Case</th>
<th>Limb Symmetry Index</th>
</tr>
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<td>2.18</td>
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<td>96.8</td>
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<td>Normal</td>
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<td>Normal</td>
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Table M-9. Total number of controls in each Lift Index, Impact Index and Movement Time case.

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