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Evaluation of Isokinetic Single-Leg Cycling as a Rehabilitation Exercise Following Anterior Cruciate Ligament Reconstruction Surgery

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EVALUATION OF ISOKINETIC SINGLE-LEG CYCLING AS A REHABILITATION
EXERCISE FOLLOWING ANTERIOR CRUCIATE LIGAMENT
RECONSTRUCTION SURGERY

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Bioengineering

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by
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ABSTRACT

The anterior cruciate ligament (ACL) is one of the most commonly injured ligaments, with over 250,000 injuries per year in the United States. Its primary function is to limit anterior tibial translation when the quadriceps muscle group contracts to extend the knee. Previous studies have found that ACL-deficient individuals avoid use of the quadriceps in the injured limb as a means of limiting anterior movement of the tibia in the absence of a functioning ACL. This altered gait pattern has been found to persist in the period following ACL reconstruction surgery, and inhibits the ability of patients to return to full quadriceps strength during physical therapy. A study by Hunt et al. investigated the existence of quadriceps avoidance in stationary, isokinetic cycling, a common rehabilitation exercise, and found that the injured individuals not only practiced avoidance of the quadriceps, but avoidance of the entire limb as well. This is possible because a large increase in output from one limb can effectively maintain the necessary cadence required in isokinetic cycling. From these results, a study was designed to investigate the effectiveness of isokinetic single-leg cycling in increasing quadriceps strength. Ten control and seven ACL-reconstructed subjects participated in an IRB-approved study that consisted of a series of 15 second cycling trails in isokinetic mode at 75 rpm, while kinematic, kinetic, and electromyographic data of the lower limbs were collected, with the trials including both double-leg cycling and single-leg cycling. It was hypothesized that there would be an increase in quadriceps muscle activity, peak knee extensor moment, and knee joint power in single-leg cycling when compared to double-leg cycling. Results of the study, although not statistically significant ($p<0.05$), hinted at the possible effectiveness of isokinetic single-leg cycling in increasing quadriceps use. A

trend in data demonstrated that given a specific limb power, more quadriceps muscle force would be generated in the single-leg task when compared to the double-leg task. Future studies should investigate the muscle activation patterns associated with single-leg cycling, and should involve a testing protocol that assesses the performance of ACL-reconstructed individuals at multiple time points in physical therapy.

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CHAPTER ONE:

INTRODUCTION

Background

The anterior cruciate ligament (ACL) is one of the most commonly injured

ligaments in the human body. Currently, there are approximately 250,000 injuries each

year in the United States. (Dai, Herman, Liu, Garrett, & Yu, 2012) The rate of incidence

of ACL injury varies between sports and between genders, with the highest rates of injury

occurring in collegiate soccer, collegiate basketball and recreational skiing, and the

majority of injuries occurring in women. (Prodromos, Han, Rogowski, Joyce, & Shi,

2007). Following injury, athletes must undergo reconstructive surgery to replace the torn

ligament. To regain normal motions and strength in the injured leg, they must then go

through a rehabilitation program under the guidance of a physical therapist. However,

literature has shown that these programs are not always successful in achieving full

recovery. (Arangio, Chen, Kalady, & Reed, 1997; Arms et al., 1984; Keays, Bullock-

Saxton, Keays, & Newcombe, 2001; Kowalk, Duncan, McCue, & Vaughan, 1997;

Paterno, Ford, Myer, Heyl, & Hewett, 2007; Williams, Snyder-Mackler, Barrance, Axe,

& Buchanan, 2004) One major concern in the rehabilitation program is bringing the

quadriceps back to full strength. Weak quadriceps muscles can affect gait of the patient,

inhibiting their progression during recovery. Research must focus on determining why

patients cannot achieve full strength and how therapy can address this in the future.

Location, Structure, and Function of the ACL

The knee is one of the largest joints in the body. It provides mobility and plays a major role in supporting the body during dynamic and static activities, which also contributes to making it the most complex joint. The knee complex consists of two main articulations: the tibiofemoral joint and the patellofemoral joint. The tibiofemoral joint is the interaction between the distal end of the femur and proximal end of the tibia. The patellofemoral joint is the interaction between the patella and the femur. Two fibrocartilaginous joint discs, called menisci, sit on top of the tibial condyles and act as shock-absorbers for the tibiofemoral joint. The meniscus also aids in distributing weight forces and reducing friction within the joint. Surrounding these bones is the joint capsule, which helps stabilize the knee. The capsule is a thin, fibrous sac of synovial fluid, and is attached to the condyles of the tibia and femur as well as surrounding muscles. This fluid helps lubricate the joint and allows for smooth motion. (Levangie et al., 2001)

Ligaments in the knee are responsible for restricting or controlling unwanted motion. This includes excessive knee extension, adduction/abduction of the tibia, anterior/posterior motion of the tibia under the femur, medial/lateral rotation of the tibia under the femur, and combinations of anteroposterior displacements and rotations of the tibia. The medial (MCL) and lateral collateral ligaments (LCL), located on either sides of the knee, help resist hyperextension. The cruciate ligaments are positioned in the center of the knee joint within the articular capsule. The anterior cruciate ligament (ACL) connects the anterior portion of the tibia to the posterior portion of the femur by passing under the transverse ligament and attaching to the inner aspect of the lateral femoral

condyle. The posterior cruciate ligament (PCL) attaches to the inner aspect of the medial femoral condyle and extends to the posterior portion of the tibia. (Levangie et al., 2001)

The main structure of the ACL is composed of type I collagen bundles that are separated by type III collagen fibrils. The ACL possesses an avascular fibrocartilaginous zone with type II collagen located on the anterior side of the ligament which runs along the intercondylar fossa. It is believed that this fibrocartilaginous area arises from high shear and compressive stresses that occur when the knee is in full extension. These collagen bundles are grouped into two bands: the anteromedial band (AMB) and the posterolateral band (PLB), which attach to the anteromedial and posterolateral portions of the tibia, respectively. Changes in length of the AMB and the PLB describe the function of each band during joint motion. For example, at 0° of knee flexion, the AMB is at its shortest and the PLB is at its longest, indicating the AMB is lax, offering the ACL the least restraint to motion in this position, and the PLB is taut, offering the most restraint to motion in this position. The opposite is true when the knee is in 90° of flexion: the AMB is taut and acts as the restraining portion of the ligament, and the PLB is lax and does not act as a restraint. (Levangie et al., 2001)

The main function of the ACL is to prevent anterior translation of the tibia on the femoral condyles. It also aids in restraining varus and valgus stresses within the knee, especially when a collateral ligament is damaged (Grood, Suntay, Noyes, & Butler, 1984; Mills & Hull, 1991; Nielsen, Rasmussen, Ovesen, & Andersen, 1984). Injury to the ACL occurs mostly when the knee is flexed and the tibia is in some sort of rotation. The ligament appears to be in high tension as it wraps around the PCL during medial tibia rotation and as it stretched around the lateral femoral condyle during lateral tibia rotation.

(Feagin & Lambert, 1985) Due to their positioning, the PLB incurs the most damage in knee extension, and the AMB in knee flexion. (Cabaud)

Reconstruction Techniques and Graft Types

Injury of the ACL is based on a grading scale of 1 to 3. A grade I injury indicates a minor sprain of the ligament, usually involving minimal damage to some of the connective tissue fibers. A grade II injury is a more severe sprain and is characterized by a visible tear in the ligament. In most cases, both of these injuries are treated with bracing and some physical therapy. Surgery is highly recommended to reconstruct the ACL for grade III injuries, which are complete ruptures of the ligament, since these tears remove stability and full function of the knee.

The current procedures used to surgically correct a ruptured ACL involve replacing the torn ligament with an autograft or allograft. An autograft is derived from the patient's own body, and the two most commonly used are the bone-patellar tendon-bone (BPTB) and hamstring tendon. The hamstring tendon is typically composed of both the gracilis and semitendinosus tendons. An allograft is derived from the tissue of another individual of the same species, and typical allografts used in ACL reconstruction include the Achilles tendon, BPTB, hamstring tendon, quadriceps tendon bone, tibial tendon bone, and tensor fascia lata. There are advantages and disadvantages to each type of graft, but the BPTB autograft is widely considered the "gold standard" for ACL replacement. (Chang, Egami, Shaieb, Kan, & Richardson)

The basic surgical procedure for an ACL replacement follows a standard method. Under anesthesia, the surgeon performs range of motion tests on the patient's knee prior

to any surgical incisions to confirm the presence of a torn ACL. These typically include the Lachman test and the anterior drawer test, both of which assess the amount of anterior movement of the tibia in relation to the femur. Incisions are then made on the knee for arthroscopic cannulas to be inserted. A camera is inserted to visually confirm the ACL tear and check for any other injuries, such as meniscal tear, that will need to be repaired during the surgery. The intercondylar notch is debrided to clear the area for the new graft to be inserted. Tunnels are drilled in the locations in which the ACL attaches to both the femur and tibia to allow for the graft to be placed. This is typically performed by first drilling through the proximal medial portion of the tibia to create a complete tunnel, and then passing the femoral guide through this tunnel to reach the intercondylar notch. Here, the femoral tunnel is created by beginning at the posterior portion of the notch and drilling proximally and laterally. The graft is passed through the tunnels, and the ends are secured within the tunnels with interference screws or other securing tools. (Larson & Kweon, 2005; Palmeri & Bartolozzi, 1996; Trojani, Sané, Coste, & Boileau, 2009; Yasuda et al., 2004)

The major differences in the surgical procedures for ACL reconstruction are due to the type of graft used. Autografts first must be harvested from the patient before the reconstruction begins. For the BPTB graft, the surgeon makes a vertical incision on the knee to harvest the middle third of the patellar tendon. The graft is removed with the bony plugs attached, which are derived from the patella and the tibia. (Palmeri & Bartolozzi, 1996) For the hamstring tendon graft, the tendons for the gracilis and semitendinosus muscles must be located and harvested. These tendons are then fashioned together by the surgeon in the operating room through the use of sutures to create a

double bundle structure before graft placement. Allografts are already ready to use, so no harvesting has to be performed in the operating room. Another main difference between procedures is the mechanism used for securing the ends of the graft. Allografts and BPTB autografts have bony plugs on each end, so typically interference screws are used to secure both ends. This is able to work well because the screw along with the bony plug creates a total diameter larger than that of the tunnel. Hamstring tendons, however, have no bone attached. Some surgeons choose to loop the hamstring tendon around a fixed screw at the end of the femoral tunnel and bring the two ends of the graft together with a screw in the tibial tunnel to create a 4-string graft. Other methods include using an endobutton for suspensory fixation of the graft in the femur. (Larson & Kweon, 2005; Trojani et al., 2009; Yasuda et al., 2004)

The allograft method avoids donor-site morbidity in the patient, generally allows for a shorter rehabilitation period and a faster recovery of quadriceps strength post-surgery due to the fact that it allows for less trauma to occur for the patient since a tissue graft does not have to be removed in addition to the procedure. (Stringham, Pelmas, Burks, Newman, & Marcus, 1996; Sun et al., 2011) However, this method does increase the risk of disease transmission, and allografts generally have decreased mechanical properties when compared to native ACL tissue. These lowered mechanical properties are due to sterilization techniques, such as gamma radiation, which has been shown to decrease the ultimate tensile strength of grafts and increase its rate of rupture when compared to non-irradiated grafts. (Fideler, Vangsness, Lu, Orlando, & Moore; Stringham et al., 1996; Sun et al., 2011) The mismatch of donor and patient age has also

been shown to have an influence over the success of the graft, indicating that age does effect the mechanical properties of the ACL over time. (Stringham et al., 1996)

Autografts are more widely used in ACL replacement surgery, comprising approximately 70-80% of the grafts used in these surgeries. (Chechik et al., 2013) The more commonly used BPTB graft is advantageous because it has very similar mechanical properties to the ACL. The BPTB graft is only slightly less stiff than the ACL with an average stiffness of 210 N/mm compared to the ACL with an average stiffness of 242 N/mm. (Woo, Wu, Dede, Vercillo, & Noorani, 2006) The autograph has a similar ultimate tensile strength to the ACL, with their average values at 1784 N and 2160 N, respectively. Most significantly, however, is the energy required to bring both the graft and the intact ACL to failure. They are almost identical, both having an average of 12.8 Nm of energy required for rupture. (Noyes, Butler, Grood, Zernicke, & Hefzy, 1984) Other advantages of the BPTB include its strong fixation due to bone-to-bone contact and its quick healing of the bone plugs within the tunnels. (Gobbi, Mahajan, Zanazzo, & Tuy) However, there can be donor site morbidity, atrophy of quadriceps, patellar femoral pain, and patellar tendonitis. The hamstring tendon graft is a double bundle structure, similar to the intact ACL, comprised of the semitendinosus tendon and the gracilis tendon. The structure of this type of graft and the fact that it has a cross sectional area similar to that of the ACL allows it to have similar biomechanical properties to that of the native tissue. It has been reported that the use of the hamstring tendon is associated with less anterior knee pain and better knee extension. Some disadvantages include donor site morbidity and the lack of strong bone to graft fixation. (Chechik et al., 2013; Jansson, Linko, Sandelin, & Harilainen)

However, there is still no guarantee that these reconstruction procedures can ensure the strength of the graft matches that of the native tissue. The odds of allograft rupture are about 4 times higher than that of autograft rupture. (Kaeding et al., 2011) Reconstruction techniques have an effect on the stable fixation of the graft. Previous studies have shown that anatomic fixations of hamstring tendon grafts and use of bone plugs with patellar tendon grafts help the most in preventing slippage of the graft within tunnels. (Scheffler, Südkamp, Göckenjan, Hoffmann, & Weiler, 2002)

Physical Therapy Programs

Physical therapy programs are required to regain full range of motion (ROM) of the knee and full strength of the muscles surrounding the injured knee after surgical reconstruction. Recent programs follow a more accelerated schedule with patients returning to physical activity around 6 months post-operatively, which has been shown to have better patient outcome. These programs can be divided in 4 phases: phase 1 (1 week post-op), phase 2 (2-9 weeks post-op), phase 3 (9-16 weeks post-op), and phase 4 (16-22 weeks post-op). Each phase focuses on achieving separate goals in order to progress to the following phase. In phase 1, the focus is on decreasing swelling and inflammation in the knee and increasing range of motion. Compression wraps and bracing along with cryotherapy are usually advised at this stage to help with postsurgical pain. Passive and active ROM exercises are implemented through the safe ranges of closed chain (CC) exercises (0°-60° safe range) and open chain (OC) exercises (90°-40° safe range). It has been shown that moving towards full weight-bearing within 10 days post-op improves strength of the quadriceps. In phase 2, the goals include increasing flexion ROM,

strengthening quadriceps and hamstrings, increasing neuromuscular control, and normal gait retraining. Advised exercises include isokinetic exercises, such as stationary cycling to work on ROM, isotonic strength training in the CC and OC safe ranges aimed at increasing quadriceps strength, static and dynamic balance training and plyometrics to work on neuromuscular control, and walking/jogging under observation by physical therapist to retrain gait. In phase 3, patients focus on further strengthening muscles while maintaining full ROM, as well as increasing neuromuscular control. Similar exercises to those in phase 2 are used, but with a larger emphasis on increasing resistance as opposed to endurance. In the final phase, the goal is to maximize the strength and endurance of the muscles and increase agility through sport-specific exercises. Patients must pass a series of tests, including the VAS (Visual Analog Sale), the IKDC (International Knee Documentation Committee Subjective Knee Form), hop tests, and isokinetic tests, at the end of the physical therapy program in order to return to sports. Passing involves achieving full ROM, the hop tests are at least 85% compared to the uninjured leg, the quadriceps and hamstrings strength are at least 85% compared to the uninjured leg, and the difference in hamstring/quadriceps strength ratio is less than 15% compared to the uninjured leg. (van Grinsven, van Cingel, Holla, & van Loon, 2010)

CHAPTER TWO:

LITERATURE REVIEW

Quadriceps Avoidance Following ACL Injury

The altered biomechanics of the lower limbs following ACL injury has been widely studied. In 1990, Berchuck et al. investigated the kinematics and kinetics of subjects with unilateral ACL deficiency in walking, jogging, and ascending and descending stairs. Results showed that there was a substantial difference in the magnitude of the knee flexion moment between the deficient leg and the uninvolved leg during walking, with a reduction of 140% in the ACL deficient limb. Berchuck et al. suggested this large reduction was due to the patients' efforts to reduce the amount of quadriceps contraction, since the contraction of this muscle group is directly related to the internal and external moments produced to flex the knee. (Berchuck et al., 1990) This quadriceps avoidance gait was only prevalent in walking, where the knee flexion angle reaches about 20°, and not in jogging and stair-climbing, where the flexion angle reaches about 40° and 60°, respectively. This is most likely due to the fact that when the knee is in a low degree of flexion (between 0° and 45°), any contraction of the quadriceps tends to displace the tibia anteriorly, placing strain on the ACL. (Arms et al., 1984; Daniel et al., 1985; Grood et al., 1984; Renström, Arms, Stanwyck, Johnson, & Pope) Therefore, the hamstrings must act to pull the tibia posteriorly to prevent uncomfortable anterior tibial translation when the knee is flexed. It is believed that the hamstrings, instead of the quadriceps, are activated more in the gait of ACL-deficient individuals in order to avoid painful walking.

This avoidance weakens the muscles and inhibits the ability of the patient to restore full function of the injured limb.

Altered Biomechanics and Muscle Activity Following ACL Reconstruction

The findings of Berchuck et al. are supported by numerous studies of individuals with fully ruptured ACLs. This has also sparked an investigation into the altered biomechanics of individuals with reconstructed anterior cruciate ligaments (ACLR) to determine if the factors associated with quadriceps avoidance persist following surgical treatment. These factors include a reduced net knee joint extensor moment, reduced activity of the quadriceps, and increased activity of the hamstrings.

The results of various exercise tests on ACL reconstructed individuals have shown that the movements of these limbs do not return to normal, healthy motion following surgery. Devita et al. looked at individuals at 3 weeks and 6 months following a BPTB replacement surgery and accelerated rehabilitation program, and found that the ACL reconstructed individuals walked with normal kinematics at the 6 month mark, but joint torques and powers did not improve completely. Results indicated that these ACL-injured subjects used a larger hip extensor torque and a smaller knee extensor torque to produce more work at the hip and less at the knee when compared to the healthy group. (Devita et al., 1998) Another study found that individuals at around 6 months post-operatively exhibited a reduction in the peak moment, power, and work in the reconstructed knee when ascending stairs. (Kowalk et al., 1997) Paterno et al. found that female athletes still displayed biomechanical limb asymmetries in drop vertical jump tasks at 2 years post-operatively. (Paterno et al., 2007)

Atrophy of the quadriceps proves to be a prevalent issue following ACL reconstruction. Previous studies have reported that injured limbs have an approximate 10% loss in muscle mass in the ACLR limb compared to the uninvolved limb and strength deficits of 10-30% up to several years post-op. (Arangio et al., 1997; Williams et al., 2004). The amount of force produced from the quadriceps at 6-8 months out of surgery has been shown to decrease as much as 28%. (Eriksson et al., 2001; Keays et al., 2001). Inadequate strength of this muscle group contributes to altered gait patterns following anterior cruciate ligament reconstruction, and it is believed that a rapid return to full quadriceps strength would contribute more to a full recovery. (Lewek, Rudolph, Axe, & Snyder-Mackler, 2002)

Current Study Development

The results of these studies overwhelmingly show that patients who undergo ACL reconstruction may not attain normal function in the injured limb after a rehabilitation program. These injuries affect more than 120,000 athletes in the US every year, and only two-thirds of those that undergo reconstruction are able to return to sports within a year. (Ardern, Webster, Taylor, & Feller, 2011; Frank & Jackson, 1997; Majewski, Susanne, & Klaus, 2006) It is estimated that 25% of those that do return will injure their knee a second time. (Hui et al., 2011; Leys, Salmon, Waller, Linklater, & Pinczewski, 2012; Shelbourne, Gray, & Haro, 2009) Patients may practice quadriceps avoidance in the early period of physical therapy if this compensatory mechanism was developed in the period of time between injury and surgery. If this avoidance persists throughout the rehabilitation program during cycling exercises, patients may never return to full

function. Therefore, it is imperative that exercises in physical therapy following surgery succeed in strengthening the quadriceps in order to restore normal gait, which in turn is expected to help prevent re-injury.

A recent study by Hunt et al. investigated the presence of quadriceps avoidance in ACL-deficient individuals during stationary, isokinetic cycling. It was hypothesized that the injured limbs would exhibit reduced net knee joint extensor moments and reduced quadriceps muscle activity, which was supported by the data, but the results did not entirely conclude that this was due to avoidance of the quadriceps muscle group. They reported that subjects were practicing a type of limb attenuation by outputting more work from the uninvolved limb to maintain the necessary cadence. (Hunt, Sanderson, Moffet, & Inglis, 2003)

Hunt et al. had hypothesized that cycling may be a good alternative model to study quadriceps avoidance, since cycling and walking have some similarities; they both require each limb to alternate movements of propulsion, and they both have comparable patterns of muscle activation and joint kinematics. (Gregor, Cavanagh, & LaFortune, 1985; Mohr, Allison, & Patterson, 1981; Winter, 1983) However, the study by Berchuck et al. reported that quadriceps avoidance was only prevalent in walking, and not in jogging or stair climbing, where knee flexion angles are greater. (Hunt et al., 2003, Berchuck et al., 1990) Knee flexion angles in cycling typically reach 60° or more, similar to stair climbing, which would indicate that cycling may not be an exercise that would even cause quadriceps avoidance.

Isokinetic stationary cycling is a common exercise in ACL rehabilitation. (van Grinsven et al., 2010) Cycling is a closed kinetic chain exercise and is intended to help

restore normal motion of the knee and improve range of motion. Isokinetic exercise is specifically defined as the shortening in length of a muscle or muscle group when it contracts at constant speed. To truly experience isokinetic exercise, opposing forces need to be able to quickly change resistance in order for the muscle to change its length at a constant speed throughout a muscle contraction. Some stationary bicycles that have programmable settings for isokinetic exercises can accomplish this type of activity. Previous studies have advocated the use of isokinetic exercises in ACL rehabilitation for their effectiveness in functional performance and for their safety. The force that opposes movement in concentric contractions theoretically should not exceed the force generated by the limb (Tsaklis & Abatzides, 2002). For these reasons and the possibility that the knee flexion angles in cycling may not allow for quadriceps avoidance, the present study is investigating the effectiveness of an isokinetic single-leg cycling exercise in increasing quadriceps activation and use.

CHAPTER THREE:

METHODS

Subjects

Seven ACL-reconstructed subjects (5 males, 2 females) participated in this study.

Subject information, including age, height, and body mass can be found in **Table 1**

below. These subjects were tested between 10 and 22 weeks out of surgery and had full

knee range of motion of the injured limb. All subjects and their physical therapists signed

an IRB-approved informed consent form prior to testing (APPENDIX A) and were made

aware of all risks and discomforts associated with the testing. Five ACLR subjects had

received a bone-patellar tendon-bone (BPTB) graft, while the remaining two had received

a hamstring tendon graft. This was a revision ACL surgery for one subject (female,

age=22, height=172.7cm, mass=60.3 kg) due to failure of the previous hamstring tendon

graft that was put in place 5 years prior. The replacement for the more recent surgery was

a BPTB graft.

Ten control subjects (5 males, 5 females) participated in the study as well. All

subjects signed an informed consent form acknowledging they had no history of

cardiovascular problems or previous lower limb injury. No statistically significant

differences in age (p>0.05), height (p>0.05), or body mass (p>0.05) were found between

the control group and ACL group.

Subjects were mostly recruited through word of mouth. Flyers were also posted in

physical therapy centers in surrounding towns and around Clemson University campus

(APPENDIX B). In order to create incentive, a modification was made to this IRB-

approved study to allow for compensation to be given in the form of $50 Amazon gift cards. These were given to the last four ACL subjects tested.

Group	Age [years]	Height [cm]	Body Mass [kg]
Control	21.3 (1.6)	171.0 (8.9)	69.7 (9.2)
ACL	22.1 (3.2)	174.2 (8.8)	70.8 (10.9)

Table 1. *Mean values for subject information of the Control Group and ACL Group.*
(Standard error values are listed in parentheses)

Protocol

The protocol for this study was previously approved by the Furman University IRB. Subjects performed a randomized series of 15-second cycling trials on a stationary lode ergometer in isokinetic mode at 75 rpm. A total of 18 trials were completed for each subject, including 6 with double-leg cycling, 6 with right-leg cycling, and 6 with left-leg cycling. Real-time biofeedback of quadriceps muscle activity was shown to the subjects for half of these trials (3 double-leg, 3 right-leg, and 3 left-leg trials). Each trial began from a complete stop (t=0 seconds), and the subjects cycled until the researchers told them to stop (t=15 seconds). Subjects were instructed to cycle at the maximum output they were able to give, and researchers collecting data at the time of testing gave encouraging words to the subject throughout the duration of the trial. Researchers gave a

10 second warning and a 5 second warning at 5 and 10 seconds into the trial,

respectively. A break of 2-3 minutes was given between trials to prevent fatigue. No

subject was unable to complete the 18 trials due to fatigue, pain, or uncomfortability.

Data Collection, Processing, and Analysis

Subjects performed the cycling trials on an Excalibur Sport Lode Ergometer (Part

#925900, Lode B.V., Groningen, Netherlands) in isokinetic mode set at 75 rpm. Seat

height was adjusted to the height of the subject's greater trochanter, and distance between

the pedal and crankshaft was consistent between pedals and between subjects. Subjects

remained seated and kept hands on the handlebars throughout all trials (**Figure 1**). The

bike clip pedals were each equipped with an ATI force/torque transducer (ATI Industrial

Automation, Apex, NC, USA) that collected tri-directional force exerted on the pedals

during the trials. The analog signals collected through the force/torque sensors were

filtered with a Butterworth lowpass filter with a default frequency cutoff of 6 Hz. These

signals were then converted from Volts to Newtons. For the single-leg cycling trials, the

opposite pedal was removed from the bike and a counterweight of 97 N was added to

assist in creating momentum for the contralateral pedal during the upstroke phase of

single-leg cycling (Thomas, 2009). The leg not involved in the trial rested on an elevated

step directly behind the bike.

Figure 1. *Subject in seated position on ergometer.*

Kinematic data was collected through the Pro-Reflex MCU 240 8-camera system (Qualisys AB, Gothenburg, Sweden) at a capture rate of 240 Hz. Kinematic markers were placed on the following locations for each limb: iliac crest, posterior superior iliac spine, greater trochanter, lateral knee joint space, medial knee joint space, lateral malleolus, medial malleolus, proximal heel, distal heel, lateral heel, head of first metatarsal, head of

second metatarsal, and head of fifth metatarsal. In addition, four tracking markers were placed on both the lateral thigh and lateral shank. These locations were chosen in accordance with pervious marker set guidelines (van Sint Jan, 2007), and an example of this setup on the subjects is seen in **Figure 2**. Four markers were also placed on each pedal, one on its axis, one on its medial side, one on its lateral side, and one on its anterior side, to create pedal coordinate systems. Marker trajectories were labelled using Qualisys Track Manager (Qualisys AB, Gothenburg, Sweden). Motion files were exported to C3D format for inverse dynamics to be performed in Visual 3D (C-Motion Inc., Germantown, Maryland USA) to determine joint moments, joint powers, and linear impulses of the pedals. Moments and powers were normalized to subject body mass. Moments were resolved to the proximal coordinate system. For example, the right knee moment was resolved to the right thigh coordinate system. Joint power was calculated as the dot product of the joint moment and joint angular velocity. Linear impulses were calculated as an integration of the magnitude of the resultant pedal force in Newtons over the specified time period of the downstroke of the pedal.
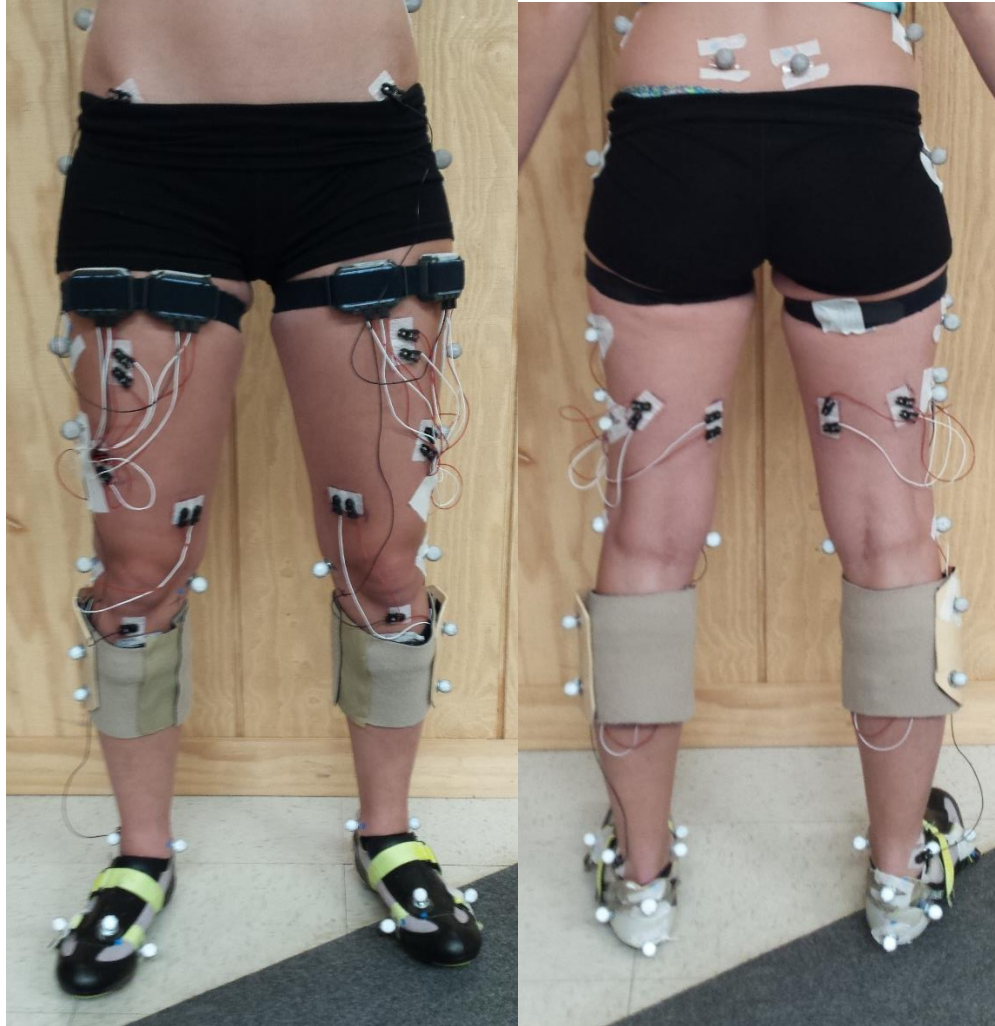
Figure 2. *Placement of kinematic markers and electrodes.*

Electromyography (EMG) was collected for six muscles on each leg, including

the vastus lateralis, vastus medialis, rectus femoris, biceps femoris, semitendinosus, and

gastrocnemius. Electrodes were placed on each leg according to the Seniam model

(APPENDIX C) and connected to BioNomadix EMG transmitters (BioPac Systems Inc.,

Goleta, California, USA), as seen in **Figure 2**. Data was collected, processed, and

analyzed in AcqKnowledge (Biopac Systems Inc., Goleta, California, USA). A bandpass

filter was applied to all data with a high frequency cutoff at 500 Hz, a low frequency

cutoff at 10 Hz, and a Q factor of 0.707. Data was normalized to the maximum

contraction for each muscle found in the testing period. Integrated EMG of this

normalized EMG was derived for each muscle with a reset period of 0.8 seconds, which

is equivalent to the time of one rotation of the bike at 75 rpm.

Statistical Analysis

All statistical tests on data were performed in JMP (SAS Institute Inc., Cary, NC

USA) using a repeated measures analysis of variance. A simple model was used to

investigate the effect of leg dominance in the Control group, and another simple model

was used to look at the effect of biofeedback. A third model was developed to compare

the Type (Double or Single) x Leg (left or right) x Group (Control or ACL) differences in

the two subject populations. Specific comparisons were examined between the one limb

of the Control group and the ACLR limb of the ACL group for ankle, knee, and hip joint

powers, ankle, knee, and hip moments, linear impulses of the pedals, quadriceps muscle

activity, and hamstrings muscle activity.

Delimitations

This study only included subjects from the ACLR population that were within 22

weeks out of surgery in order to study a representative population of patients who are in

physical therapy following ACL reconstruction surgery. This excludes ACL-deficient

individuals who have not undergone reconstruction surgery to replace the ligament. The

protocol was designed to study the possible effectiveness of a single-leg cycling

rehabilitation exercise. The kinematic, kinetic, and EMG variables were selected for

analysis based off of previous literature review of quadriceps avoidance after ACLR and cycling studies with ACLR populations.

Trials were excluded from analysis if subjects moved to an unseated position on the bike or removed their hands from the handlebars. Data was excluded if subjects stopped cycling before the 15 second trail was completed, or if any hardware involved malfunctioned during testing.

CHAPTER FOUR:

RESULTS AND DISCUSSION

The purpose of this study was to determine if single-leg cycling would be an

effective rehabilitation exercise after ACL reconstruction surgery in terms of

strengthening the quadriceps. This was done by examining the biomechanical changes

that occur between double- and single-leg cycling and determining if these changes

indicate that single-leg cycling increases use of the quadriceps, thereby effectively

strengthening those muscles. Integrated electromyography of three quadriceps muscles

and two hamstring muscles were collected over the entire rotation of the pedal to examine

the changes in muscle activity in single-leg cycling. Peak ankle, knee, and hip extensor

and flexor moments, peak ankle, knee, and hip power, and linear impulse of the pedals

during the downstroke were collected as well. Due to the fact that the quadriceps muscle

group is the active muscle group during the downstroke phase, kinematic and kinetic data

were focused on that phase of the cycle. We hypothesize that single-leg cycling will

prompt a greater use of the quadriceps when compared to double-leg cycling.

Specifically, we expect to see increased quadriceps activity, increased knee joint power,

and an increased knee extensor moment.

Effect of Leg Dominance

The first analysis was performed on the Control group to investigate the effect of

leg dominance on all variables of interest. If a large effect exists, there may be a

significantly large difference in performance between limbs. The results, outlined in

Table 2, show that leg dominance had a significant effect on the majority of variables of interest (p<0.01). This could be due to better proprioception in the dominant limb, which would allow subjects to cycle with smoother movement of the lower limb, influencing kinematic variables. The dominant leg also outputted significantly more force on the pedals, demonstrating the greater strength of the dominant healthy leg compared to the non-dominant healthy leg. However, this was not supported by the EMG data, which indicated more activity occurred in two of the quadriceps muscles (vastus lateralis and vastus medialis) of the non-dominant leg. Even so, with these results, it can be concluded that it is not possible to compare the ACLR leg of the ACL group to any leg of the Control group. Five of the seven subjects tested in the ACL group had surgery in their dominant leg. To account for the two who had surgery in their non-dominant leg (28% of the ACL group), we included data of three non-dominant legs of Control subjects (30% of Control group) along with data of seven dominant legs of the Control subjects to create a comparable Control group leg.

Effect of Leg Dominance in Control Group			
Variable	**Non-Dominant Leg**	**Dominant Leg**	**p-value**
Peak ankle extensor moment [N*m/kg]	-0.02 (0.12)	-0.04 (0.12)	0.3659
Peak ankle flexor moment [N*m/kg]	-0.74 (0.15)	-0.85 (0.15)	<0.0001
Peak knee extensor moment [N*m/kg]	1.38 (0.26)	1.95 (0.26)	<0.0001
Peak knee flexor moment [N*m/kg]	-1.85 (0.23)	-2.14 (0.23)	0.0014
Peak hip extensor moment [N*m/kg]	4.51 (0.60)	5.74 (0.60)	<0.0001
Peak hip flexor moment [N*m/kg]	-6.10 (0.66)	-7.34 (0.66)	<0.0001
Peak ankle power [W/kg]	3.28 (0.70)	3.73 (0.70)	0.0036
Peak knee power [W/kg]	8.43 (1.33)	12.17 (1.33)	<0.0001
Peak hip power [W/kg]	21.86 (3.16)	26.42 (3.16)	<0.0001
Linear impulse [N*s]	155.6 (16.7)	167.1 (16.7)	0.0014
Biceps femoris activity [mV/s]	4.17 (0.29)	4.24 (0.29)	0.5792
Rectus femoris activity [mV/s]	3.87 (0.37)	4.03 (0.37)	0.2507
Vastus lateralis activity [mV/s]	5.01 (0.15)	4.60 (0.15)	0.0026
Vastus medialis activity [mV/s]	5.85 (0.27)	5.02 (0.28)	<0.0001
Semitendinosus activity [mV/s]	5.34 (0.26)	5.35 (0.26)	0.9641

Table 2. *Effect of leg dominance on variables of interest (standard error values are listed in parentheses)*

Effect of Biofeedback

The second analysis was also performed solely on the Control group to determine if the presence of biofeedback of quadriceps muscle activity during the cycling trials had any impact on variables of interest. We hypothesized that the existence of biofeedback

would increase muscle activity. The results of this test are shown in **Table 3.** Although there is a slight increase in muscle activity when biofeedback was present, there was no variable in which it had any significant effect ($p < 0.01$). Due to limitations of the study, these trials only lasted for 15 seconds, and at times subjects chose not to look at the biofeedback signals shown during the trials. We believe that if trials lasted for a longer period of time, such as 60 seconds or more, and if subjects were more encouraged to focus on the signals, biofeedback may have a significant effect.

Effect of Biofeedback in Control Group			
Variable	**No Biofeedback**	**Biofeedback**	**p-value**
Peak ankle extensor moment [N*m/kg]	-0.03 (0.12)	-0.03 (0.12)	0.55
Peak ankle flexor moment [N*m/kg]	-0.79 (0.15)	-0.81 (0.15)	0.55
Peak knee extensor moment [N*m/kg]	1.69 (0.26)	1.65 (0.26)	0.66
Peak knee flexor moment [N*m/kg]	-1.98 (0.23)	-2.02 (0.23)	0.70
Peak hip extensor moment [N*m/kg]	5.10 (0.60)	5.17 (0.60)	0.74
Peak hip flexor moment [N*m/kg]	-6.58 (0.66)	-6.87 (0.66)	0.19
Peak ankle power [W/kg]	3.44 (0.67)	3.58 (0.67)	0.40
Peak knee power [W/kg]	10.32 (1.34)	10.36 (1.34)	0.93
Peak hip power [W/kg]	23.25 (3.17)	25.12 (3.17)	0.04
Linear impulse [N*s]	158.8 (16.7)	163.9 (16.7)	0.16
Biceps femoris activity [mV/s]	4.16 (0.29)	4.24 (0.29)	0.56
Rectus femoris activity [mV/s]	3.93 (0.37)	3.97 (0.37)	0.78
Vastus lateralis activity [mV/s]	4.78 (0.16)	4.85 (0.16)	0.61
Vastus medialis activity [mV/s]	5.44 (0.26)	5.52 (0.26)	0.63
Semitendinosus activity [mV/s]	5.27 (0.26)	5.43 (0.26)	0.34

Table 3. *Effect of biofeedback on variables of interest (standard error values are listed in parentheses)*

Muscle Activity of Quadriceps and Hamstrings

Integrated EMG values were obtained for quadriceps and hamstrings muscles for both the Control and ACL groups in double and single leg cycling, as seen in **Figure 3**. When looking at the changes that occur in the Control limb when switching to single-leg

cycling from double-leg cycling, it is apparent that there is a significant decrease in activity in the quadriceps muscles and a significant increase in the hamstrings muscles. The upstroke in cycling is accomplished with force generation from the hamstrings that induces knee flexion and brings the pedal to top dead center. The force required to complete this movement would be much larger without a counter limb to assist in the upstroke, and the counterweight that was implemented in this protocol may not have been successful in mimicking that counter force, which would explain the drastic increase in hamstrings muscle activity for the healthy limb. When looking at these changes within the ACL group, however, there is not much of a difference in muscle activity for either the quadriceps or hamstrings. This indicates that the muscle groups are generating the same force in both conditions to accomplish the tasks, as opposed to the control, which generated more muscle force from the hamstrings to accomplish the single-leg cycling task.
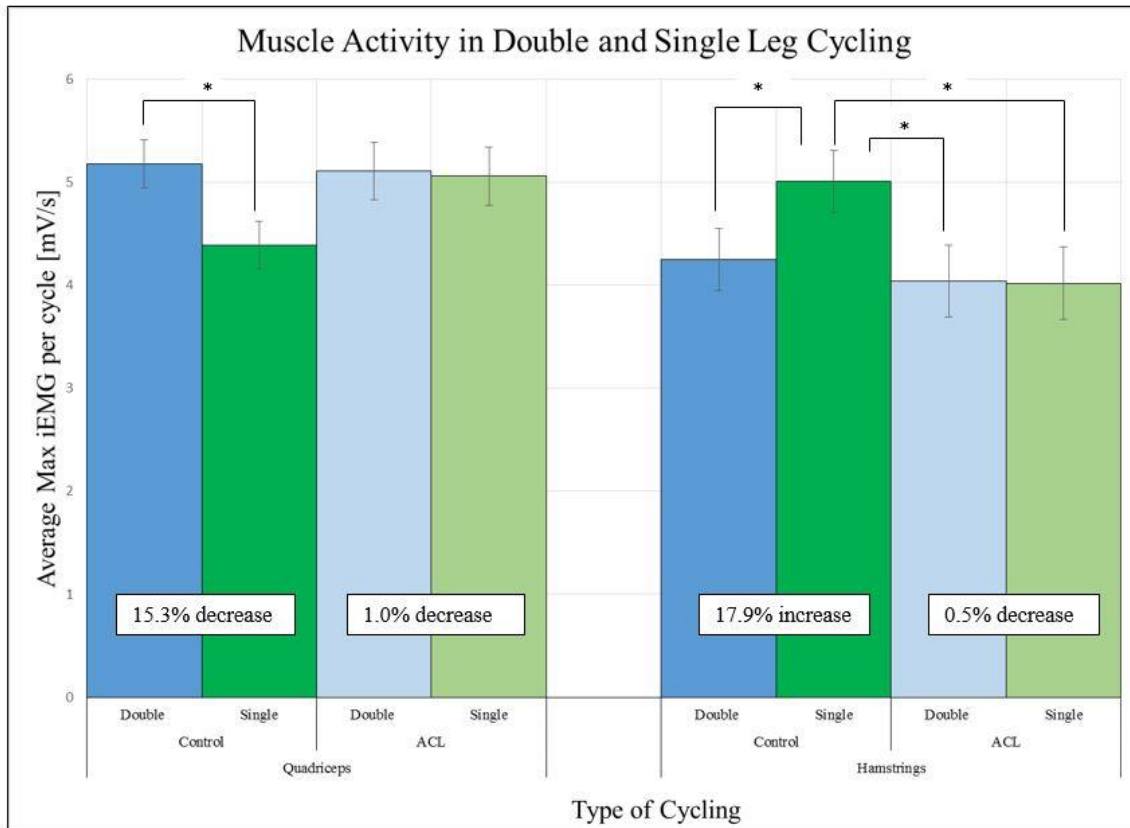
Figure 3. *Average integrated EMG (significance (p<0.05) is noted with an asterisk)*

Joint Powers, Joint Moments, and Pedal Impulses

Joint power is a good indicator of the amount of energy each joint is generating to complete the cycling task in each condition. **Figure 4** outlines the results of peak joint power data collected in the downstroke for the ankle, knee, and hip, as well as total peak joint power in this phase. There is no significant difference in power for any joint between double and single leg cycling, but some obvious trends exist. In the Control group, there is a decrease in ankle power and in hip power, as well as an increase in knee joint power in single leg cycling compared to double leg cycling. However, in the ACL group, there is a decrease in power in all joints. There is a noticeable difference in the magnitude of hip power between the control limb and ACLR limb, with the ACLR hip

generating more power in both double- and single-leg cycling. Looking at total joint power of these limbs, **Figure 4** illustrates the decrease in ACLR limb power is almost twice that of the control limb power in single-leg cycling compared to double-leg cycling. These results point towards the difficulty in generating the same amount of energy when cycling with just one limb than with both limbs.

Joint power is calculated as the product of joint moment and joint angular velocity. To further understand why these trends are present in joint power, it is necessary to see what changes are occurring in joint moments. Because the motion of the knee and hip are both in extension during the downstroke phase, the moments influencing peak joint power here are the peak extensor moments. As seen in **Figure 5**, the same trends are present in knee and hip extensor moments. The control limb exhibits an increase in peak knee extensor moment in single-leg cycling and a decrease in peak hip extensor moment, while the ACLR limb exhibits a decrease in both variables. The magnitudes of the hip moments are also much larger in the ACLR limb than the control limb.
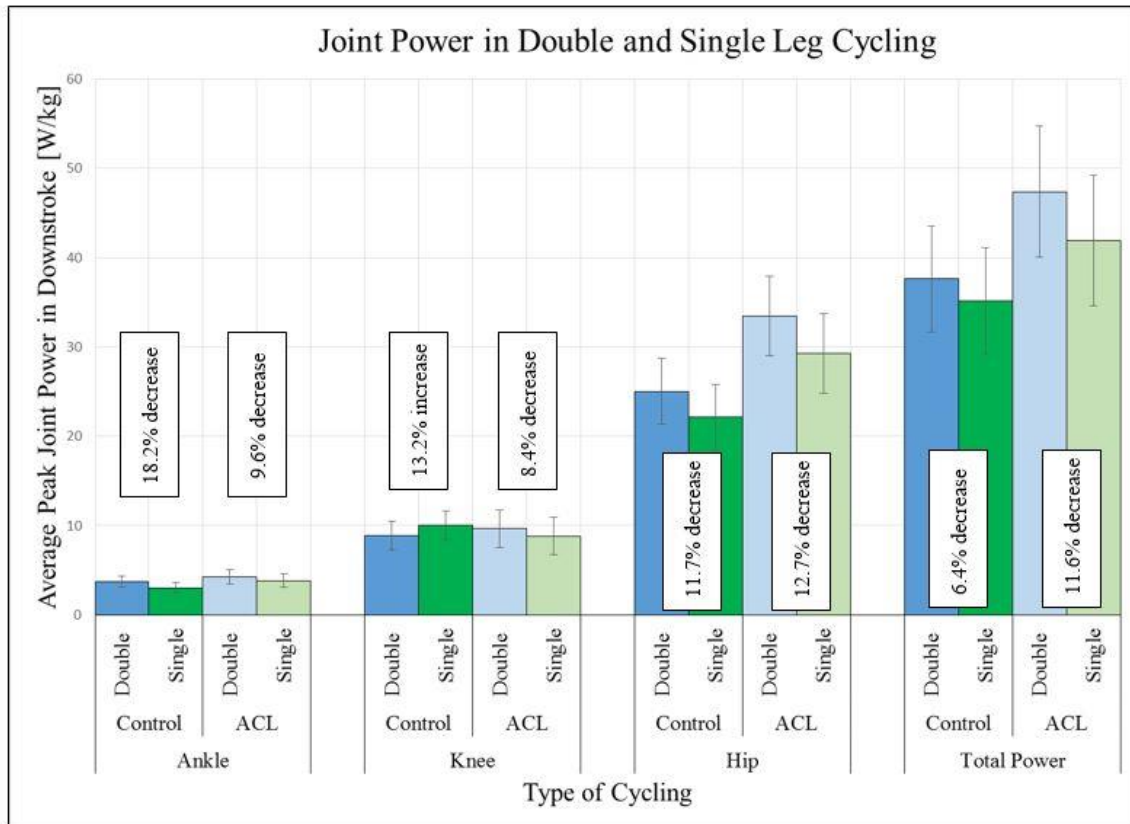
Figure 4. *Average maximum joint power in the downstroke (no significance was found; p<0.05)*
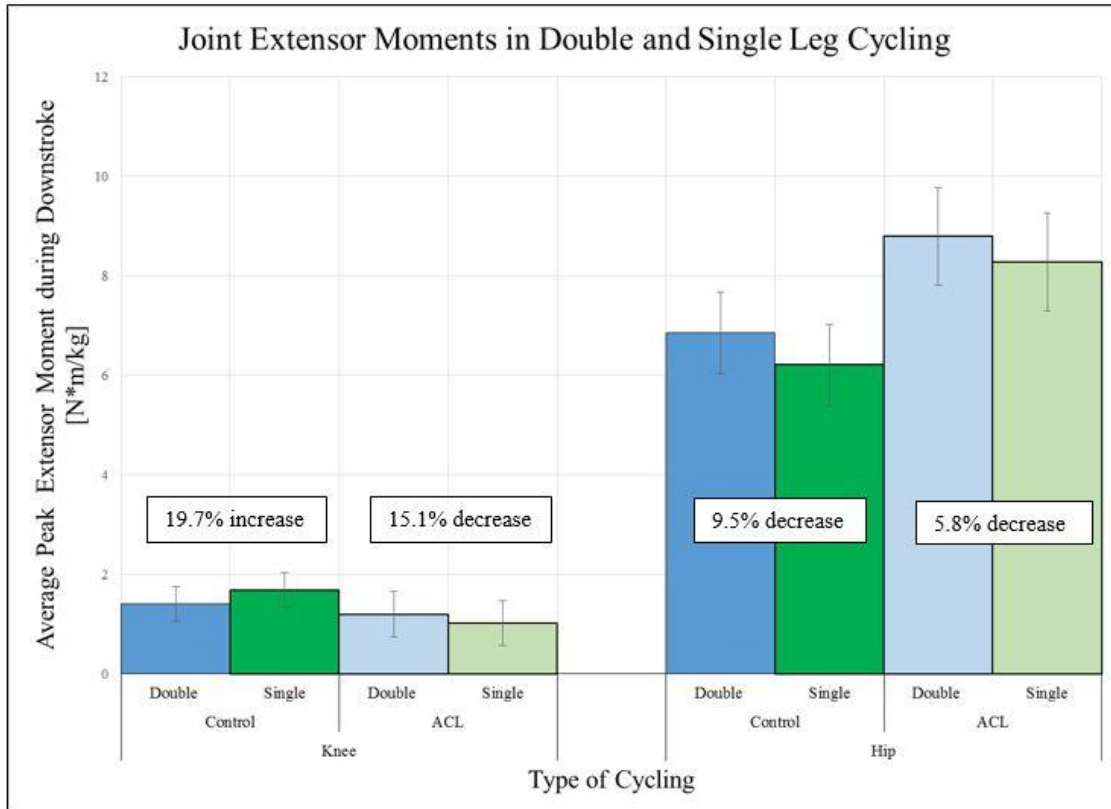
Figure 5. *Average peak joint extensor moments in the downstroke (no significance was found; p<0.05)*

Linear impulses of the pedals were calculated for the downstroke phase. The results are outlined in **Table 4**. For both the control limb and ACLR limb, there is a reduction in linear impulse in the single-leg task compared to the double-leg task, with slightly higher impulses generated from the ACLR limb compared to the control limb. Since the resultant pedal force is influenced by the amount of power generated by the corresponding limb, these results support the results of the joint power data.

	Linear Impulse in Downstroke [N*s]	
	Double Leg Cycling	Single Leg Cycling
Control Group	161.9 (17)	152.4 (17)
ACL Group	177.2 (19)	165.8 (19)

Table 4. *Average linear impulse in the downstroke (no significance was found; p<0.05)*

Discussion

Quadriceps avoidance in the gait of ACL-deficient individuals has consistently been defined in previous literature by a reduced knee extensor moment. Joint moments are influenced by two factors: the joint segments' mass moment of inertia and the joint's angular acceleration. The mass moment of inertia is directly related to muscle forces that allow for extension or flexion of a joint. As the mass of a joint segment increases, the force produced by muscles to flex or extend the joint increases as well. The quadriceps muscle group generates a force to induce a knee extensor moment, while the hamstrings group generates a force to induce a knee flexor moment. These past studies on quadriceps avoidance have reported a reduced knee extensor moment, implying a reduction in force generated by the quadriceps, hence the term "quadriceps avoidance". Hunt et al. found that this reduced moment also existed in cycling for ACL-deficient subjects. However, their findings indicated that these subjects almost entirely avoided use of ACL-deficient limbs and the counter limb supplied more energy and power to complete the cycling tasks. The present study investigates the ability of single-leg cycling to promote a greater knee extensor moment, in turn increasing activation of the quadriceps, and thereby exercising that muscle group and increasing its strength.

It was hypothesized that single-leg cycling would cause greater quadriceps muscle activity. Results from this study show that single-leg cycling actually decreased the amount of activity from all three quadriceps in the control group, and did not

significantly change the activity of the quadriceps in the ACL group. It seems that the hamstrings of the control limb produced more force in the single-leg task to make up for the large decrease in quadriceps force. These changes are not well explained by the results of the kinematic and kinetic data. With a reduction in quadriceps activity in the single-leg task, a reduction in knee extensor moment would be expected, but the results indicate that there is a slightly larger knee extensor moment. To better understand the kinematic mechanisms associated with this trend, it would be best to investigate the activity of these muscles during the downstroke and upstroke separately. However, due to limitations of the study, this type of analysis was not possible. The control limb may be experiencing co-contraction of the quadriceps and hamstrings during one complete rotation on the bike that results in a greater net activity from the hamstrings as opposed to the quadriceps. For this study, it was assumed that the quadriceps are the major contributor of muscle force for the downstroke and the hamstrings are the major contributor of muscle force for the upstroke. Suggestions for future studies include investigating the activation patterns of the quadriceps and hamstrings during the two phases of single-leg cycling to determine if this assumption is true.

The ACLR limb provided the same amount of muscle activity in both the quadriceps and hamstrings in both types of cycling trials. This pointed towards the idea that these muscles were able to output the same amount of force, regardless of changing cycling conditions. Again, this data reflects the activity occurring throughout entire rotations, and does not distinguish activity solely in the downstroke phase.

It was hypothesized that single-leg cycling would cause an increase in peak knee extensor moment as well as peak knee joint power. Although not significant, this pattern

is present in the healthy control limb, but not present in the ACLR limb. The results also indicate that both control and ACLR limbs do not produce the same amount of total joint power in the single-leg task compared to double-leg task. This is supported by the pedal impulse data, which reports a decrease in total power transferred to the pedals. Although the amount of power of the ACLR limb decreases for the single-leg task, the EMG data proves the quadriceps muscles are still generating the same amount of force. In other words, the ACLR limb is generating more muscle force per any given limb power in single-leg cycling than double-leg cycling.

In addition, the healthy limb shows a slightly larger extensor moment in the knee in the single-leg trials, demonstrating that a single-leg exercise like this, if implemented into a rehabilitation program, may induce more knee extension and more quadriceps force as patients progress through physical therapy and reach a healthy limb status. This increase in joint moment was not exhibited by the ACL group because the testing procedure only assessed the subjects' ability to perform cycling tasks at a certain point in their physical therapy program, and did not take into account the effect of long-term exercise involving single-leg cycling on these variables. Subjects also noted that they were initially uncomfortable with the movements involved in the single-leg trials, and commented on the difficulty in completing them. Future studies should consider testing subjects multiple times throughout physical therapy, and possibly train subjects in single-leg cycling prior to testing as a way to familiarize them to the motions.

Limitations

The majority of subjects in this study were generally young and active. Therefore, the results of this study would not be comparable to patients who are older or not active. The time out of surgery when the subjects were tested varied greatly, with some subjects tested as little as 10 weeks out, and as far as 22 weeks out. If the study could be redesigned, it is suggested that subjects come in for testing multiple times during their physical therapy program to investigate how their ability to perform single-leg cycling exercises changes throughout the program.

The kinematic and kinetic variables were analyzed in the downstroke (0°-180°) and upstroke (180°-360°) of the pedal to differentiate the periods of when the quadriceps and hamstrings are responsible for the work done. However, this was not done with EMG data due to inability to differentiate downstroke and upstroke periods, so analysis was performed for 0.8 second intervals, which is equivalent to the time to complete one rotation of the bike at 75 rpm. It was assumed that subjects cycled at a constant cadence of 75 rpm, but the isokinetic mode of the Excalibur Sport has a variability of +/- 6 rpm at this speed.

The protocol was designed to test the performance of subjects over a series of 18 trials. Many variables were investigated in this study, including single-leg cycling versus double-leg cycling and the presence of biofeedback versus no biofeedback, which contributed to needing a protocol involving many trials. One shortcoming of this is that the trials could only last for 15 seconds in order to prevent fatigue of the subjects during testing.

CHAPTER FIVE:

CONCLUSIONS

The results of the study suggest that single-leg cycling may be an effective exercise in increasing the strength of the quadriceps following anterior cruciate ligament reconstruction surgery. Although no significant changes occurred, the results indicate that given a specific limb power, more muscle force will be generated from the quadriceps muscle group in single-leg cycling than double-leg cycling. The control group exhibited an increased knee flexor moment, also not significant, when changing to single-leg cycling, revealing a possible increase in quadriceps muscle force in this type of activity.

The sample size of this study was small, which limited the statistical significance of many variables of interest in this study. Subjects in this study were rather young and active, so results are not representative of the entire ACL-reconstructed population. Future studies should encompass a wider range of individuals as well as a larger number of subjects. The ACLR individuals were only tested at one point in their physical therapy program, and the phase in which each individual had reached in the program varied. When investigating the possible effectiveness of single-leg cycling in the future, it would be best to test subjects at multiple time points after ACL reconstruction surgery.

It should also be noted that muscle activation patterns may change in single-leg cycling tasks, and this phenomenon should be further investigated. Results from the EMG data were not easily explained by the kinematic results, due to differences in when data was recorded. It is suggested that future studies focus on data collection in the phase of cycling in which quadriceps muscle activation occurs in order to better understand the

relationship between muscle forces, joint moments, and joint powers during single-leg cycling, and what implications it may have for increasing quadriceps strength.

Due to limitations, the protocol for testing involved extremely short sprint cycling tests, which differs from typical rehabilitation exercises involving cycling. In physical therapy, patients will normally use a stationary bicycle to exercise for a period of 15-30 minutes. More research needs to be conducted to determine what kind of single-leg cycling protocol would be safe, effective, and applicable in a physical therapy setting.

APPENDICES

APPENDIX A:

SUBJECT INFORMED CONSENT FORM

SUBJECT INFORMED CONSENT FORM
Department of Health and Exercise Science
Molnar Human Performance Laboratory

1. Explanation of the Tests

You will be asked to participate in various tests for a total of approximately 3 HOURS in 1 day that will enable the investigator (s) to assess your muscle strength on a stationary bike ergometer.   The procedures for conducting the tests are as follows:

  a. <u>Standing Height</u> - standing height will be measured as you stand erect, with shoes off, and with your back against a stadiometer. After you inhale deeply, a square edge will be brought in contact with the top of your head and height recorded.

  b. <u>Body Weight</u> - body weight will be recorded as you stand on a weight scale, with your shoes off and clad in shorts.

  c. <u>Electromyography (EMG)</u> – Your muscles contract due to an electrical signal from your brain causing a voltage or action potential across the muscle fibers. This EMG data collection involves measuring these action potentials that are occurring in your muscles when you move. The stronger the contraction of your muscle, the higher the action potential is in your muscle. This data will be collected as you perform the cycling tests. To gather this data, 15 surface electrodes, with a 1inch x 1inch area, will be placed in specific locations <u>on each leg</u> to gather this data. One will be on your hip, 6 will be on the front of your thigh, 4 will be on the back of your thigh, 1 will be on your shin, 2 will be on your calf, and 1 will be on your ankle. These electrodes are similar to a Band-Aid, but they must be in direct contact with the skin. This means that the area where the electrode is placed must be cleaned and free of hair. This data will be blinded and kept for 1 year from the time of your study.

  d. <u>Kinematic Data</u> – This data allows us to see the forces and moments produced in each of the joints in your lower limbs. This data is collected from reflective, ball-shaped, markers that are placed on specified locations on your body. These markers are the only thing picked up by our cameras and will be used to make a virtual stick figure of your cycling tests. This data will also be blinded and kept for 1 year from the time of your study.

  e. <u>Single-Leg Cycling Tests:</u> You will be asked to perform **12 single-leg cycling tests**, (6 left and 6 right) **and 6 regular cycling tests,** (using both legs) each

lasting 15 seconds, over a 30 minute period. These tests will be performed at constant speed of 75 RPMs and you will be asked to activate your muscles as much as possible during each test. **6 single-leg cycling tests** (3 left and 3 right) **and 3 regular cycling tests** will be performed while viewing the amount of muscle activity on the muscles of the thigh.

2. Risks and Discomforts

There exists the possibility of certain changes occurring during the bike tests. They include local muscle pain and fatigue, and stress on your tendons and ligaments. To minimize these risks, we try to recruit only healthy individuals. If you feel that you do not meet the qualifications of a healthy individual, please notify the researchers immediately. If you should start to feel dizzy, lightheaded, or feel any discomfort during the testing, you should also notify the researchers immediately. Every effort will be made to minimize these risks by observations during testing.

3. Responsibilities of the Participant

You are responsible for fully disclosing requested information regarding your health status, pertinent lifestyle behaviors (usage of medications, caffeine, and tobacco, exercise habits) and psychological or physical feelings/symptoms accompanying physical exertion.

When riding on a stationary bike, there is a variable called resistance that changes how hard it is to pedal forward. The higher the resistance is on the bike, the more force you need to move the pedal forward. The power that you produce from pedaling on the bike is related to the force you push down on the pedal and the speed that you pedal. To ensure that you are not pushing yourself beyond your regular activities, you are responsible for obtaining your maximum allowable power output from a physician or physical therapist if you are currently rehabilitating from an injury.

Participants who are currently in rehabilitation after ACL surgery <u>MUST be at least 10 weeks into his/her rehabilitation program, be asymptomatic, and have full and symmetric knee range of motion.</u> If possible, test results from a KinCom dynamometer will be taken from the participant's physical therapist.

4. Benefits to be Expected

The results from the exercise tests will be used to evaluate your muscle activity and a possible method of improving your muscle activity. You will not be compensated for participating in this study.

5. Freedom of Consent

Please ask for further explanations if you have any doubts or concerns. Your permission to participate in these exercise tests is entirely voluntary. You may freely choose to deny consent or to withdraw from the testing at any time.

I _____ acknowledge that I have been thoroughly informed of and understand the procedures to be administered in this study. I am fully aware of any possible risk or discomfort that I may experience by participating in this study. My participation in this study is purely voluntary and I understand that I may withdraw from the study at any time without incurring coercion or prejudice. I acknowledge that I have no history of cardiovascular problems, especially diseases related to hypertension. I understand that a copy of this consent form and my results will be available to me upon request. I consent to participate in these tests.

_____
Signature of Subject

_____   _____
Date   Signature of Witness
_____   _____W _____
Date   Max. Power Output   Signature of Physician/Physical Therapist
                                for Single-Leg
                                Cycling at 75 RPMs

If any questions or problems arise related to your participation in this study, contact Dr. Randy Hutchison at PAC 4F or 864-884-7162.
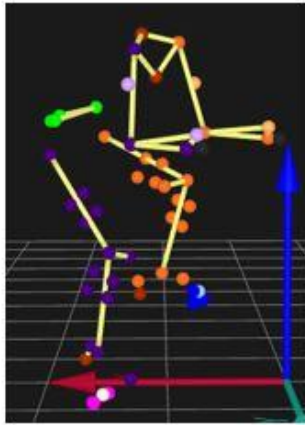
These electrode placements are based off http://seniam.org/sensor_location.htm, which is the SENIAM model for placement of electrodes. Each muscle should have two electrodes each when finished. <u>Each pair of electrodes should be 20mm apart</u>, which is the distance between electrodes if the edge of one whole electrode stick-on square is right next to the edge of the metal circular part of the other electrode.

VL (Vastus lateralis):

- Have the subject sitting with their knee in slight flexion and the upper body slightly bent backward.
- **Location**: Placed at <u>2/3 on the line from the anterior superior iliac spine</u> to the <u>lateral side of the patella</u>. Place the electrodes (20mm apart) in the <u>direction of the muscle fibers</u> (see the direction of the muscle fibers on the poster of the muscles of the body- <u>about 20 degrees</u> off of this line angled in towards the knee).


VM (Vastus medialis):

- Have the subject sitting with their knee in slight flexion and the upper body slightly bent backward.
- **Location**: Placed <u>80% on the line between the anterior superior iliac spine and the joint space in front of the anterior border of the medial ligament</u>. Place the electrodes (20mm apart) <u>PERPENDICULAR to this line</u>.

RF (Rectus Femoris):

- Have the subject sitting on a table with the knees in slight flexion and the upper body slightly bend backward.
- **Location:** Placed 50% on the line from the anterior spina iliaca superior to the superior part of the patella. Place the electrodes in the direction of this line
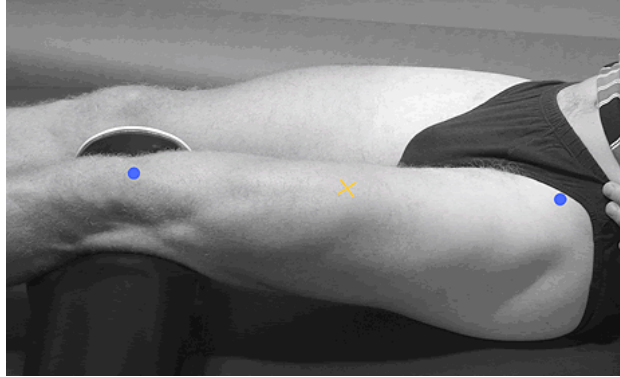
ST (Semitendinosus):

- Have the subject lying on the belly with the face down and the thigh held down on the table, in medial rotation, and the leg medially rotated with respect to the thigh. The knee needs to be flexed to less than 90 degrees.
- **Location:** Placed at 50% on the line between the ischial tuberosity and the medial epicondyle of the tibia. Place the electrodes in the direction of this line
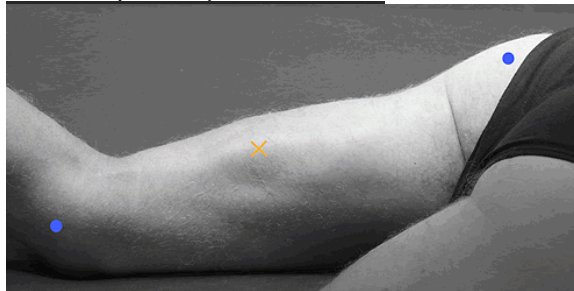
BF (Biceps femoris):

- Have the subject lie on their stomach face down and thigh down and have the knees slightly flexed (less than 90°). Put the thigh in slight lateral rotation and the leg in slight lateral rotation with respect to the thigh.
- **Location**: Placed at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia. Place the electrodes (20mm apart) in the direction of this line.

GM (Gastrocnemius medialis):

- Have the subject lay on their stomach with their foot extended and slightly propped, and have the subject flex their calf.
- **Location**: Placed on the most prominent bulge of the muscle. Place the electrodes (20mm apart) in the direction of the leg.

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