A Thesis
entitled

Inter-limb Differences in Quadriceps Strength & Voluntary Muscle Activation

by
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Context: Lower extremity neuromuscular assessment is important for detecting possible injury risk and determining return to play criteria following injury. Evaluation of isokinetic strength and voluntary activation testing are both commonly performed to detect inter-limb neuromuscular quadriceps deficits, yet it is unknown if inter-limb deficits in these two measures provide similar information regarding quadriceps function.

Objective: Determine if inter-limb deficits differ between measures of isokinetic quadriceps strength and voluntary activation at 90° of knee flexion in healthy participants. Secondarily, we sought to determine the relationship between inter-limb deficits in quadriceps strength and voluntary activation. Design: Crossover. Setting: Research laboratory. Participants: Twenty-five participants (11 Males, 14 Females, age=25.08 ±4.67 years, height=172.88±7.74cm, weight=67.04±10.67kg) with no history of knee injury volunteered for the study. Interventions: Independent variables included testing measure (isokinetic strength and voluntary activation) and sex (male and female).
The order in which testing measures were performed was randomly assigned. Isokinetic strength was performed at 60°/second through the full range of motion. Voluntary activation was assessed by administering a supramaximal electrical stimulus during a maximal voluntary isometric contraction at each target angle. **Main Outcome**

**Measures:** Isometric quadriceps strength was determined by extracting torque measurements at 90° of knee flexion, while voluntary activation was measured via the central activation ratio. Inter-limb difference scores for each measure were expressed as an absolute value percentage of the dominant leg ((non-dominant - dominant leg)/dominant leg). A 2x2 repeated measures analysis of variance was used to determine differences in inter-limb deficits between measures and sex. A Pearson product moment correlation was used to assess the relationship between deficits at each joint angle. An a priori level of significance was set at \( P < 0.05 \). **Results:** No differences in inter-limb deficits were found between sexes (\( F_{1, 23} = .001; p = .977 \)), and there was no significant sex by testing method interaction (\( F_{1, 23} = .003; p = .955 \)). However, there was significant difference in inter-limb deficits between testing methods (\( F_{1, 23} = 4.140; p = .05 \), and deficit of isokinetic torque was greater than CAR. There was no significant correlation between muscle activation and isokinetic muscle strength tests (\( r = -.056, p = .79 \)). **Conclusion:** Inter-limb deficits were higher for quadriceps isokinetic strength compared to voluntary activation. Interestingly, inter-limb deficits between measures were not strongly correlated, suggesting that these measurements may be evaluating completely different phenomena within the neuromuscular system. While future data is still needed to determine how deficits in each measure relate to physical function and long-term outcomes in injured populations, this may be evidence to suggest that athletic trainers
should utilize information from both isokinetic strength and voluntary activation tests to compile a complete assessment of quadriceps neuromuscular function.
This thesis is dedicated to my wonderful wife, Sunhee who she always advises me to make the best decision ever. Without her devotion and support, I cannot complete this thesis. Thanks God to bring her to me.
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Chapter 1

Introduction

Commonly dominant and non-dominant limbs are distinguished by two factors: the dominant limb is used more often than the non-dominant and is more comfortable to use. This sharp distinction between the two upper limbs may produce differences in performance and muscle strength between the hands. The empirical evidence clearly proves that this dominance/non-dominance between upper limbs exists as performing even simple tasks with non-dominant hand is very difficult. People can move and lift some objects with both hands equally; however dominant hand usage more often occurs with movements like writing, throwing, and catching. Athletes especially distinguish dominant and non-dominant upper-limb usage, and typically the dominant side is used more often. This also means the dominant side has more chance for injury, even overuse injury. Whereas dominance is clearly defined for upper limbs, this is not the case for lower limbs.

A significant difference in muscle strength and muscle activation caused serious imbalances in the lower extremity that may affect lower extremity biomechanics. However, when T’Jonck et al. compared plantar and dorsal flexor strength between leg
dominances, they found that there was no significant difference between legs. According to Guette and colleagues\textsuperscript{6}, whereas the effect of upper limb dominance on the circadian rhythm was cleared; there was no significant difference for the lower limbs. In spite of these studies, other sources showed that higher ball speed was created by preferred legs among soccer players.\textsuperscript{7,8,9,10} Sadeghi et al.\textsuperscript{11} defined the dominant leg as the leg used for mobilization or manipulation while the non-dominant leg supports the action. Obviously, soccer is dependent on leg movement, and although most soccer players are able to kick with both legs, they play better and kick more often with their preferred leg. Clagg and colleagues\textsuperscript{12} performed kinetic analyses for soccer kicking with female collegiate soccer players and found that in order to create higher ball speed, the non-dominant leg must be planted to stabilize and support the kicking leg. The amount of hip and knee rotation on the planted leg determined how fast and how forcefully the player was able to kick.

Quadriceps voluntary activation deficits are common following a variety of knee joint injuries.\textsuperscript{13,14,15} Rehabilitation following knee injuries focuses on increasing strength, muscle activation, and co-ordination prior to returning to the sport or to normal activities of daily life.\textsuperscript{16,17} However, quadriceps strength deficits and muscle activation failure exist in patients following rehabilitation programs.\textsuperscript{18,19} Pietrosimone et al.\textsuperscript{15} suggested that the motor system may utilize suboptimal motor recruitment patterns to accomplish tasks in an inhibited state. Williams et al.\textsuperscript{20} also explained that patients with ACL injuries had altered muscle activation patterns and quadriceps insufficiencies in both static and dynamic tasks. Inappropriate muscle activation of the quadriceps may lead to kinematic changes at the knee and possibly create episodes of giving-way. It remains possible that strength of the quadriceps could be improved with traditional therapeutic exercise
programs while muscle activation remains decreased, thus making the underlying neural impairment and possibly adding to the risk of early joint degeneration.\textsuperscript{13,14,21}

Volitional quadriceps activation deficits are associated with inhibition specific to the motor neuron recruitment and firing frequency.\textsuperscript{22} It has been hypothesized that quadriceps inhibition may be a limiting factor in rehabilitation following joint injury.\textsuperscript{13} It is reasonable to suggest that arthrogenic muscle inhibition (AMI) may be the underlying cause of the strength and gross neuromuscular deficits found in people with knee injuries.\textsuperscript{23} The inability to adequately activate the quadriceps muscle may alter lower extremity function which may be a contributing factor in early joint degeneration and articular cartilage breakdown.\textsuperscript{24}

Two testing methods, isokinetic torque and the central activation ratio (CAR), are commonly used to evaluate muscle strength and muscle activation, respectively. T’Jonck et al.\textsuperscript{5} said that an isokinetic device provides an objective and standardized protocol to evaluate muscle strength. In clinical studies, kinetic muscle strength testing also has been used to assess quadriceps torque deficits in individuals with ACL injuries and reconstruction.\textsuperscript{18,25,26,27} Torque (a measurement of angular force) decreases may be representative of underlying neuromuscular deficits.\textsuperscript{14} CAR is commonly used to assess volitional quadriceps activation and is measured by superimposing a supramaximal electrical stimulation on a maximal volitional contraction. The volitional torque is expressed as a percentage of the torque produced by the quadriceps following stimulation of the inhibited musculature.\textsuperscript{28,29} Authors\textsuperscript{13,14,21,30} have reported lower CAR in the involved leg compared to the uninvolved leg in people with ACL reconstruction. However, it is unknown if injured legs with deficits in CAR are different than muscle
strength deficits in healthy subjects. It also remains unknown whether deficits in quadriceps muscle activation and muscle strength are similar in patients with good health. Similar deficits in quadriceps strength and activation may suggest that either of these measurements can be used clinically to determine neuromuscular deficits to prevent future knee injuries while differences in leg deficits between measurement techniques may provide evidence that these values are providing different information about the neuromuscular status of the quadriceps.

**Operational Definition**

Muscle Activation: the ability of the motor neuron to excite the muscle tissue via motor unit recruitment and firing frequency.

Muscle Strength: the amount of force a muscle can produce with a single maximal effort

Isokinetic: pertaining to the force of a human muscle that is applied during constant velocity of motion

Arthogenic Muscle Inhibition (AMI): ongoing reflex inhibition of musculature surrounding a joint after distension or damage to structures of that joint

**Statement of the Problem**

There has been a substantial amount of research devoted to strength assessments and muscle activation to evaluate quadriceps muscle function. However, no research has been performed to determine if both measurements are providing similar information. It
is uncertain how these measurements may differ between the dominant and non-dominant leg with healthy subjects.

**Statement of the Purpose**

The purpose of this study was 1) Determine if inter-limb differences were affected by testing methods (muscle strength test and muscle activation test) and by sex at 90 degrees of knee flexion. 2) Determine if there was a difference between testing methods and leg dominance. 3) Determine if inter-limb differences in isokinetic torque was related to inter-limb differences in CAR.

**Hypotheses**

H$_1$: Inter-limb differences will not be affected by testing method or sex.

H$_2$: The leg dominance will not affect CAR or isokinetic strength testing.

H$_3$: Inter-limb differences in CAR will not be correlated with isokinetic strength.

**Significance of the Study**

The isokinetic muscle strength test is commonly used to determine a return to activity after knee joint injuries.\textsuperscript{15,21,24,30,31,32,33} Although patients are able to participate to their pre-injury level, it does not mean that the deficit of muscle activation is resolved. The incidence of osteoarthritis is increased five to fifteen years following knee joint injuries because quadriceps strength deficits may change knee kinematics and kinetics.

The purpose of rehabilitation is the restoration of function of muscles which surround the knee joint. Therefore, it is important to look at quadriceps deficit through CAR testing because this test evaluates motor neuron recruitment. It is also important to know how
isokinetic strength and muscle activation test results relate to each other in order to
determine whether both tests should be performed before returning an athlete to
participation following an injury.
Chapter 2

Literature Review

Anterior cruciate ligament (ACL) injury is common with various sporting activities including soccer, basketball, football, and skiing. Every year more than 100,000 ACL reconstructions (ACL-R) are performed in the United States and 4000 in Sweden which comprises 50% of ACL injured patients in both countries. Therefore, a vast amount of research has been conducted related to ACL injury in the realm of treatment, rehabilitation, and surgery. Neuromuscular deficits following ACL injury or surgery remains one of the major concerns for clinician. In this chapter, it covers how unilateral knee injury affects on quadriceps strength and muscle activation.

Altered Quadriceps Control associated with ACL pathologies

The primary function of ACL is the resistance to anterior tibial translation on a fixed femur. Therefore, the objective of ACL-R is the restoration of the knee function to move properly and prevent excessive tibial translation.

Several researchers have reported patients with ACL injury exhibit muscle weakness after rehabilitation and even after ACL-R. The weakness of quadriceps caused the poor function of knees, and it led to changes in knee kinematics and kinetics.
Furthermore, the consequence of these changes increased incidence (more than 50% of ACL-R patients) of the degeneration of the knee articular cartilages which is called Osteoarthritis (OA).\(^{34,35,37,38,39}\)

Palmieri-Smith et al.\(^{40}\) looked at the influence of quadriceps inhibition associated with knee joint effusion during a single-legged drop landing. In this study, subjects performed drop landing with 4 conditions: no effusion, lidocaine, low effusion (30 mL), and high effusion (60 mL). Ground reaction force (GRF) and electromyography (EMG) were collected for this study. According to their analysis, Palmieri-Smith et al. found greater amounts of inhibition of vastus medialis and vastus lateralis were presented in high effusion, but medial hamstring muscle activity was also greater in high effusion. The peak knee flexion and net knee extension was lower in high effusion, but the peak GRF was great in high effusion. They concluded that in high effusion condition, quadriceps muscle group was inhibited which altered knee mechanics. Therefore, inhibited quadriceps caused to increase GRF because inhibited quadriceps could not absorb compressive force.

Courtney and colleague\(^{41}\) conducted a study comparing proprioception and somatosensory evoked potential (SEP) and muscle synergies during gait. Seventeen subjects with ACL-deficiency (ACL-D) were allocated to one of two groups: non-copers who were not able to perform any sports activity because of numerous incidents of giving way, and copers who were able to perform all sport activities fully. Seven subjects without ACL-D were also recruited as a control group during gait test. Four different types of tests were performed for this study: maximum voluntary isometric contraction (MVIC) testing of the quadriceps, somatosensory evoked potential (SEP) testing, knee
proprioception testing, and gait testing during treadmill walking. Upon reviewing the data collected, Courtney and colleagues\textsuperscript{41} found that ACL-D subjects altered SEPs and neuromuscular patterns to achieve the high level of activity. These alterations also changed CNS adaptation which affected a change in motor output to maintain joint stabilization.

Drechsler et al.\textsuperscript{19} conducted a study to look at the change in muscle strength and muscle activation after ACL-reconstruction (ACL-R). Thirty one subjects who had undergone bone-patellar tendon bone ACL-R were recruited. There were also two different control groups: twenty physically inactive subjects and five active subjects. A knee ligament arthrometer was used to measure the total amount of passive anterior tibial displacement for ACL-R group. This group also took self-assessment of 10 cm visual analogue scale before and right after a maximal voluntary contraction (MVC) test; a specially designed water knee volumeter was used to measure knee volume. The MVC test was taken during 90 degrees of knee flexion to knee extension on both injured and uninjured legs with 100, 75, 50, 25% level of MVC for all groups. One way ANOVA indicated that there was a significant difference between groups at all levels of MVC contraction at one and three month; post hoc tests also showed that injured limbs were significantly lower than other groups at one and three month. The result of knee laxity side to side differences at one and three months after surgery showed that knee was stable, knee volume side to side differences showed that there was significant reduction at three month.

Suter and colleagues\textsuperscript{29} performed six weeks and six months following up studies after arthroscopy knee surgery with thirty subjects. Subjects participated in side to side
assessments of an isometric knee extensor contraction test, muscle inhibition test, and visual analogue pain scale (VAS) to look at the relationship between the progression of muscle inhibition and knee pain after knee surgery. Their data analysis showed that compared to prior surgical intervention, the knee extensor movement was decreased at six weeks post surgery, but it was increased at six months post surgery. Although muscle inhibition of the involved leg was decreased at six months post surgery, it was significantly higher than the uninvolved leg. They concluded that quadriceps muscle strength was decreased at six weeks post surgery because of muscle atrophy, but its muscle strength was increased progressively by rehabilitation and physical activity. In contrast to this the quadriceps muscle inhibition was still higher than uninvolved leg because muscle activation was not fully restored during rehabilitation.

Konishi et al.\textsuperscript{42} looked at the gamma loop dysfunction of quadriceps muscle with patients who had ACL-R. The subjects were given a maximal voluntary contraction (MVC) test and electromyographic signal (I-EMG) before and after twenty minutes of vibration stimulation. The vibration stimulation was manually applied to induce attenuation of Ia afferents. The result of MVC and I-EMG showed a significant difference was detected in short term group (< 12 month after ACL-R), but no difference in long term group (> 18 months after ACL-R). Konishi’s group concluded that ACL injury induces attenuation of Ia afferents from mechanoreceptors in ACL to \( \gamma \) loop, and it might cause decreases in MVC and I-EMG. However, ACL was recovered over long period which means the mechanoreceptors would be re-innervated in reconstructed ligaments.
Williams and colleagues\textsuperscript{20} conducted a study which looked at the quadriceps dysfunction with ACL deficiency (ACL-D) patients. EMG data from six muscles (rectus femoris, vastus medialis, vastus lateralis, semitendinosus, gracilis, and biceps femoris-longus) were collected while subjects did dynamic and static tasks. The dynamic task was cyclic knee flexion and extension in the last 30\textdegree{} of knee extension and isometric target matching protocol was used for static task. One way ANOVA indicated that there was a significant difference between subjects with ACL-D and uninjured subjects in both dynamic and static tasks. The subjects with ACL-D showed the poor quadriceps muscle control, and the vastus lateralis showed significant differences compared to other muscles. They concluded that ACL-D caused quadriceps dyskinesia, and it might change whole knee kinematics and kinetics, then furthermore, it might be a factor for the degeneration of knee articulation.

All of previous studies concluded that the muscle activation of quadriceps muscle group was decreased after ACL-R or ACL-D conditions. The mechanoreceptors in ACL were lost by ACL injuries which these conditions influenced neuromuscular system. Improper processing of neuromuscular system affected on the quadriceps muscle activation that this condition changed knee kinematics and kinetics. Quadriceps muscle group has an important role on knee movement because it absorbs compressive force, so it may decrease the stress on knee articular cartilage.

**Osteoarthritis associated with ACL pathologies**

Osteoarthritis (OA) is commonly occurs among old ages, but young people who have ACL-R or ACL deficiency (ACL-D) may have this pathology earlier than its natural
sequence. More than 50% of ACL injured patients had OA five to fifteen years after the injury.\textsuperscript{32,37,39} The primary role of articular cartilage is the absorption of compression, and it makes joint moving smoothly within its designed range of motion. The cartilage also responds to dynamic hydrostatic compression which it stimulates cartilage to produce more proteoglycan contents which necessary components to make cartilage stronger.\textsuperscript{43}

Kessler et al.\textsuperscript{35} conducted a long term study with 109 patients who had ACL-rupture, and subjects were divided by bone-ligament-bone reconstruction (operation group) or conservative treatment (non-operation group). Follow-up time of this study was about eleven years, and all subjects were received the same rehabilitation program. The subjects were evaluated in three areas: function (by IKDC score and KT 1000), radiological evaluation (on the Kellgren and Lawrence score), and sports ability (on the Tegner score). In functional testing, the data showed that ACL-R group was a significantly better in both IKDC score and KT 1000. However, the risk of osteoarthritis was a higher in ACL-R group (45%) than the conservative treatment group (24%) in radiological evaluation. There was no significantly difference between both groups in sports ability test. Kessler et al.\textsuperscript{35} concluded that it was not clear, but the patella tendon was involved in knee extensor movement which absorbed the compression force acting on the knee joint, so bone-ligament-bone autograft reconstruction might change its role on the knee joint. Therefore, proper conservative treatment would be preferred because it was lower in risk of osteoarthritis.

Another study to look at the tibiofemoral OA (TF OA) in long term follow-up with ACL injured patients who had non operative treatment was done by Neuman and colleagues.\textsuperscript{32} A total of 92 subjects were recruited for fifteen years follow-up study.
According to the diagnosis of arthroscopy, only fourteen subjects had isolated ACL tear. The rest of patients suffered ACL tear in combination with other knee injuries such as meniscal injury, medial collateral ligament injury, and chondral injury. All subjects were recommended to have regular rehabilitation program, radiography, and the self-reported questionnaires (KOSS, Tegner sore, and Lysholm score) were taken for knee evaluation. The result of this study showed that 13 (16%) of 79 subjects showed TF OA in radiographic exam. Total 35 subjects were underwent meniscectomy, and 13 subjects (37%) of them showed TF OA. However, 44 non-meniscectomized subjects did not have any TF OA. 6 (35%) of 17 ACL-R subjects had TF OA, and 6 (46%) of 13 ACL-R with meniscal tear subjects had TF OA. Authors concluded that ACL-D was the factor for the degeneration of articular cartilage, however, if subjects were underwent meniscectomy or meniscal tear, they were more prevalent to have TF OA.

Meunier et al. conducted a similar long term follow-up study with ACL injured patients who had either ACL-R or non-surgical treatment. They also concluded that patients who had ACL-R had less prevalence of OA than non-surgical treatment subjects because it increased knee instability. However, meniscectomy increased its prevalence to lead to OA than without it.

All of the previous studies demonstrated that after long-term follow up, there were significantly higher chances of OA among ACL-R and ACL-D subjects. The major purpose of ACL-R was restoration of its normal function. Although subjects had regular rehabilitation programs, high percentage of subjects showed progression of OA because either ACL-R or ACL-D changed knee kinematics and kinetics. However, subjects who had meniscectomy showed more prevalence of OA than without it because it decreased
the absorption of compressive force toward between knee joints, then it might damage on articular cartilage directly.

**Arthrogenic muscle inhibition (AMI)**

Arthrogenic muscle inhibition (AMI) is an ongoing reflex inhibition of muscular structures that it diminishes motor neuron pool excitability surrounding an injured joint.\(^{13,32,34,36,37,39,44}\) Although AMI is a natural response to protect the joint from further damage by discouraging its use, it is a limiting factor for rehabilitation because it inhibits motoneuron (MN) pool of muscles surrounding knee joint.\(^{13,32,37}\)

Hopkins and Ingersoll\(^ {13}\) stated that the quadriceps would be inhibited by arthrogenic muscle inhibition (AMI). Since the motor neurons are inhibited, it decreases its ability to contract muscles sufficiently then finally muscles may decrease their strength and change the kinematics of knee movement. Improper muscle activation and changed kinematics and kinetics cause poor knee mechanism, then it would be the reason for early OA which follows after ACL-R or ACL-D. According to Pietrosimone and colleagues\(^ {30}\), when MN pool excitability is inhibited, MN recruits different motor unit to perform a task. Therefore, if patients perform rehabilitation exercise without the reactivation of inhibited muscles, it changes proper suboptimal motor recruitment patterns and increases muscle fatigue, and finally it leads to chronic muscle dysfunction.

Snyder-Mackler et al.\(^ {45}\) conducted a study which found out reflex inhibition of quadriceps muscle associated with ACL injury and ACL-R. Depending on activity level, subjects were divided into three groups. Group 1 was consisted of twenty subjects who they had been done ACL-R between one and six months after the injury. Group 2 was
consisted of twelve subjects who they had been torn ACL for three months. Group 3 was consisted of eight subjects who they had been torn ACL for two years. Two seconds after electrically generated superimposed burst, the subjects were asked to contract knee extensors maximally and data were collected by an electro mechanical dynamometer. According their analysis, there were no significant increases in superimposed burst (less than 5%) on involved and uninvolved leg in both Group 1 and 3, and the maximal force of the involved leg was 77 % and 76% of uninvolved let respectively. However, nine subjects of Group 2 showed a significant increases in superimposed burst torque (more than 5%), and the maximal force of involved leg was 76% of uninvolved leg. They concluded that ACL injuries affected sensory receptors (or mechanoreceptors) which caused reflex inhibition and decreased quadriceps motor output. Therefore, quadriceps muscle could not be activated properly.

Palmieri and colleagues\textsuperscript{46} performed an experimental knee joint effusion to induce arthrogenic muscle response. Ten healthy subjects had four conditions: needle stick, Xylocaine injection, 25 and 45 min post saline injection. All subjects received five trials of 1ms square wave pulses to tibial nerve with 10s rest intervals while they were in supine position. M-response (M max) stimuli were given to elicit an H-reflex. The subjects were also received eight trials of 80 ms pulse to tibial nerve as the same as H-reflex and M-response procedure to elicit paired reflex depression (PRD). Recurrent inhibition was applied to soleus alpha motoneurons by a conditioning H-reflex (H1) and a subsequent test H-reflex (H2). H2 was only passed along the motor fibers when there was the collision which produced by motoneurons evoked H1. Analyzed data showed that there were significant difference on recurrent inhibition and PRD with 24 and 45 min
post knee joint effusion. They concluded that the activation of quadriceps muscle was decreased by the presence of effusion because knee joint effusion inhibited reflex inhibition via recurrent and presynaptic mechanisms.

**Treatments for AMI**

An article by Pietrosimone et al. looked at the effectiveness of modalities for tibiofemoral osteoarthritis patients. Finally total 33 patients were participated for this study. The patients performed maximal isometric contraction (MVIC) on the dynamometer, and then electric stimulus was applied on quadriceps muscle group. The examiner provided a burst of superimposed stimulation when there was a maximal force plateau observed, and two acceptable trials were collected out of two to three MVIC trials. For the intervention, patients were divided three groups: the focal knee joint cooling group, transcutaneous electrical nerve stimulation (TENS) group, and control group. The focal knee joint cooling group had two 1.5 L crushed ice bag on anterior and posterior aspect of the knee joint for twenty minutes. The TENS group received continuous biphasic pulsatile current for 45 min. The subjects in control group just sat on the dynamometer for twenty minutes as other group. Central activation ratio (CAR) was calculated by dividing the force of the MVIC (F-MVIC) by force of the superimposed burst (F-SIB) plus F-MVIC. Visual analysis scale (VAS) was taken at the beginning of each time interval. According to their data analysis, TENS group had a significantly higher percentage change in CAR score at 20 min, 30 min, and 45 min. The focal knee joint cooling group also had a significantly higher percentage change at 20 min and 45 min. However, there was no significant difference between these two treatments.
Pietrosimone and Ingersoll\textsuperscript{21} also conducted another similar study which looked at the effectiveness of the focal knee joint cooling to increase quadriceps CAR. Eleven healthy subjects participated in this study. When the patients reached a force plateau, they received submaximal bursts from electric stimulator. Two high qualities of trials were collected from three at each time intervals (pre-test, 20, 30, and 45 min). During the control condition, subjects were seated for twenty minutes. The data analysis of this study showed that there was a significant higher CAR after the focal knee joint cooling at 20 min and 45 min compared to the pre-test.

Since there are ACL related injuries, AMI inhibits pre- and post synaptic reflex and it automatically decrease muscle activation around knee joint especially quadriceps muscle. These previous studies showed that TENS unit and the focal knee joint cooling decreased the AMI inhibition, and then increased quadriceps muscle activation.

**Muscle Activation Test**

The muscle activation test can show the ability of muscle recruitment, and muscle recruitment which means maximal muscle contraction. Therefore, when there is no sufficient muscle recruitment, superimposed muscle activation test will show peak muscle activation over the maximal plateau, and it will be used to calculate CAR in the measurement of side to side difference. Most studies used Grass S88 muscle stimulator to deliver superimposed burst. It produced a 100 ms train of 10 stimuli, at 100 pps, with a 0.6 ms pulse duration and a 0.01 ms pulse delay.\textsuperscript{13,31,32,40} Drechsler et al.\textsuperscript{19} used a Digitimer DS7 to deliver a constant current stimulus for twitch superimposition.
Pietrosimone and Ingersoll\textsuperscript{21} used superimposed muscle stimulator to look at how focal knee joint cooling affect on CAR. Total eleven voluntary healthy participants participated in this study. The subjects received two ice bags for twenty minutes, and control subjects just sat for twenty minutes. The electric muscle stimulator was manually applied while subjects were doing isometric contraction. The measures were collected at 4 different times (pre-test, 20, 30, 45min post-test). According to data analysis, the CAR was significantly higher after focal knee joint cooling at 20 min and 45 min post-test. This study concluded that focal knee joint cooling facilitated motor neuron pool excitability and it increased muscle activation. When muscle activation is increased, it also increases muscle strength.

Suter et al.\textsuperscript{29} conducted a study to look at quadriceps activation with patients who had ACL pathologies (ACL-D or ACL-R). Forty six patients received superimposed electrical twitch during maximal knee extension. When there was uncompleted muscle activation, the electrical stimulation evoked interpolated twitch torque (ITT). Isometric knee extensor moment was also measured by using an isokinetic dynamometer and muscle activation of each knee extensor was collected by using an EMG. The result showed that both types of knee pathologies (ACL-R and ACL-D) had significant muscle inhibition during knee extension, but ACL-D patients showed significantly higher muscle inhibition. The knee extension moment was a significantly higher in combination of knee extension and hip extension protocol compared to isolated knee extension.

Previous studies showed that superimposed muscle activation test was a valuable evaluation tool to identify muscle inhibition because completely activated muscle could
not show further peak in maximal isometric contraction. These muscle activation deficits are used to calculate CAR.

**Muscle Strength Test**

The muscle strength test is necessary to determine when injured athletes are able to return to activity after injuries, and it could be measured by one of three methods: isometric, isokinetic, and isotonic test. The maximal voluntary isometric contraction (MVIC) test is normally done by either surface EMG\textsuperscript{19,36,37,39,41,47,48} or isokinetic dynamometer.\textsuperscript{15,21,24,30,31,32,40} However, isokinetic dynamometer also can measure peak torque which the maximal amount of force used for extension or flexion of the muscle. Side to side difference of muscle strength could be measured either isometric or isokinetic testing.

Williams and colleagues\textsuperscript{20} used EMG to collect muscle activation data from subjects who they had ACL deficiency (ACL-D). Electrodes were placed on five muscles: rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), semitendinosus (ST), biceps femoris-longus (BF), and gracilis (GRA). According to their data analysis, there was improper muscle contraction on RF and VL observed during knee movement. ACL deficiency subjects were not able to allow quadriceps muscles to turn off its muscle activation during knee flexion, and this inappropriate quadriceps muscle activation might be related to further knee joint pathologies like OA.

Moisala and colleagues\textsuperscript{27} used isokinetic dynamometer to evaluate muscle strength after ACL-R. 48 ACL-R subjects (16 subjects received a bone-patellar tendon-bone and 32 subjects received a quadruple hamstring autograft) were recruited for this
study. After warming up at the bike ergometer, the subjects were secured on an isokinetic dynamometer. The ratio of the quadriceps and hamstring peak torques was measured for this study. The result of this study indicated that there were no significant differences between bone-patellar tendon- bone graft and hamstring graft on knee extension torque deficit and knee extension torque deficit. Furthermore, long term flow up (12 months and 30 months) also showed that there were no significant differences in muscle strength between grafts. They concluded that as muscle strength was increased, knee flexion and extension torque deficit was decrease in long-term follow-up.

Ageberg and Friden\textsuperscript{18} conducted a study to normalize motor function between non-ACL-R and uninjured subjects. In this study, isokinetic dynamometer was used to measure peak torques of concentric and eccentric contraction for both quadriceps and hamstring muscle. The result showed that although the peak torque in extension was higher in ACL injured subjects, the peak torque in flexion was higher in uninjured subjects. They concluded that there was no difference between non-ACL-R and uninjured subjects.

These studies showed that muscle strength was measured by either isometric contraction or isokinetic contraction instruments. EMG and isokinetic dynamometer are commonly used to measure MVIC.\textsuperscript{24,31,32,40} Isokinetic dynamometer also measure muscle peak torque in knee flexion and extension, and this data is used to determine the returning to activity. However, if there is difficulty to measure muscle strength, perhaps other measurements could be applied: muscle biopsy, magnetic resonance imaging (MRI), and computerized tomography (CT scan).\textsuperscript{49}
Conclusion

Several studies have shown that the muscle activation of quadriceps muscle was decreased by AMI associated with ACL injuries and ACL-R. Although there was no significant difference in muscle strength between injured and uninjured legs after a long period of rehabilitation program, it could not prove that there was also no significant difference in muscle activation. Pietrosimone et al.\textsuperscript{15} stated that patients were performing therapeutic exercise in an inhibited state, but it may change motor recruitment patterns to accomplish the task. This improper muscle activation may alter knee kinematics which leads to the degeneration of knee joint (OA).\textsuperscript{13,34,36,37,40,43,44}

Most of previous studies conducted muscle strength tests to find out quadriceps dysfunction related to knee injuries, and most of their analysis showed that increased muscle strength meant increased muscle contraction. However, it is unknown if the muscle activation test may show slightly different result with the muscle strength test. Furthermore, if the muscle activation test shows that there is quadriceps deficit beyond muscle strength test, it may provide more efficient clinical intervention to treat possible knee pathologies after knee injury treatment.
Chapter 3

Methodology

Subjects

Thirty young healthy subjects volunteered for this study. Five subjects were excluded because they could not perform a consistent maximal voluntary isometric contraction; therefore twenty five subjects were used in the final analysis (Table 1). All subjects voluntarily participated from the University of Toledo and surrounding area. The subjects were excluded if they had any history of lower extremity injury or orthopedic surgery, muscular abnormality, sprained knee ligaments, cancer or infection around the thigh or knee, history of heart condition or were currently pregnant (in case of female subjects). The dominant leg was determined as the leg used when kicking a ball. All subjects signed an IRB approved informed consent form before participating.

Instrumentation

A Biodex System 2 (Biodex Medical Systems, Shirley, NY) was used to measure torque output (Figure 1). The Biodex was connected to a 16-bit analog-to-digital converter (MP 150, BIOPAC Systems, Inc., Goleta, CA) with custom made coaxial cable.
A Grass stimulator (S88, Astro-Med Inc., W. Warwick, RI) was used to produce supramaximal electrical burst (Figure 2). The Grass stimulator was set up at a rate of 100 pulses per second with a .01 msec delay for 0.6 msec and a train rate of 10. The transformer stimulus isolation unit (SIU8T, Astro-Med Inc., W. Warwick, RI) was used to produce safe electric stimulation for human subjects. Therefore, one side of the SIU8T was connected to the Grass stimulator and the other side was connected to electrodes (8 × 14 cm carbon-impregnated electrodes) placed over the quadriceps as previously reported.\textsuperscript{21,30}

All data was visualized by the Acknowledge BIOPAC Software (BIOPAC Version 3.7.3 Goleta, CA).

**Independent Variables**

1. Sex
   a. Male
   b. Female

2. Testing Method
   a. Isokinetic Muscle Strength
   b. Muscle Activation

3. Limb Dominance
   a. Dominant leg
   b. Non-dominant leg

**Dependant Variables**
1. Central Activation Ratio

2. Interlimb Central Activation Ratio (CAR) deficit measured in isometric contraction \( \frac{\{\text{CAR non-dominant leg} - \text{CAR dominant leg}\}}{\text{CAR dominant leg}} \times 100 \)

3. Interlimb leg quadriceps isokinetic strength deficit \( \frac{\{\text{non-dominant leg torque} - \text{dominant leg torque}\}}{\text{dominant leg torque}} \times 100 \)

**Procedure**

This study was designed for crossover study. All subjects signed an informed consent form then subjects also filled out self-reported function questionnaires: knee injury history form. After completion of all documentation, the subjects’ weight and height were measured. Before starting testing, all subjects were required to perform a five minute warm-up on a stationary bike. Every order of testing methods and leg tested were randomly assigned.

**Muscle Strength Testing**

Subjects were secured to a Biodex dynamometer (Biodex System 2; Biodex Medical Systems, Shirley, NY) with the hip flexed between 80° to 90°. The seat was adjusted until the subject’s lateral epicondyle was even with the axis of rotation of the dynamometer. The Velcro strap of the dynamometer arm was secured below the belly of the calf muscle. The subjects were asked to cross their arms during this test. Individual full knee range of motion (flexion through extension) was set up for isokinetic testing, and then subjects performed full knee extension at a speed of 60° per second until the subject and the investigator felt comfortable with this testing. After the practice session,
subjects performed five maximal knee extensions at a speed of 60° per second. The subjects were asked to repeat two sets of five full knee extensions per each leg, and forty seconds of rest were taken between sets (Figure 3).

**Central Activation Ratio (CAR) Testing**

The biodex dynamometer was set up the same way for muscle strength testing except the dynamometer arm was locked at 90° of knee flexion for this test. Two 8 x 14 cm self adhesive stimulating electrodes were placed over the distal vastus medialis (VM) and the proximal vastus lateralis (VL) (Figure 4). The placement of these electrodes was based on previous research.\(^{21,30}\) Subjects practiced two trials each of maximal contraction (25%, 50%, and 75%) with stimulation and 100% maximal contraction without stimulation. After the practice trials, subjects performed three trials of maximal voluntary isometric contraction (MVIC) of knee extension. When the subjects reached a plateau in the quadriceps MVIC, a supramaximal electrical stimulus (10 pulse 100ms train, 125 volts, 100Hz, 0.6ms phase duration) was applied to the quadriceps via the Grass stimulator and stimulus isolation unit. The mean of two trials of maximal contraction were collected for this testing.

**Data Analysis**

Peak quadriceps isokinetic strength was assessed at 90° of knee flexion by extracting a mean force value of 10ms around the target angle (5ms to the right and 5ms to the left of the value corresponding to 90° of flexion). This number was extracted, converted into newton/meters and normalized to the subject’s body mass. Percent
strength deficit was calculated for all subjects using the following equation: **Equation 1:**

\[
\text{Equation 1: } \left( \frac{\text{non-dominant leg torque} - \text{dominant leg torque}}{\text{dominant leg torque}} \right) \times 100.
\]

CAR was calculated by dividing the force measurements of the MVIC (\(F_{\text{MVIC}}\)) by that of the force produced by the superimposed burst (\(F_{\text{SIB}}\)) plus the maximal voluntary contraction:

**Equation 2:**

\[
\text{Equation 2: } \text{CAR} = \frac{F_{\text{MVIC}}}{F_{\text{SIB}} + F_{\text{MVIC}}}.
\]

The peak force (\(F_{\text{SIB}} + F_{\text{MVIC}}\)) value and the \(F_{\text{MVIC}}\) were calculated from the mean of the two best separate trials at each time in the series, when the superimposed burst was applied. \(F_{\text{MVIC}}\) was calculated from a 0.15 second time epoch immediately prior to the administration of the exogenous electrical stimulus. Deficit scores were calculated similarly to the strength score deficits: **Equation 3:**

\[
\text{Equation 3: } \text{CAR deficits} = \left( \frac{\text{Non-dominant CAR} - \text{Dominant CAR}}{\text{Dominant CAR}} \right) \times 100 .
\]

**Statistical Analysis**

Data was analyzed through SPSS 15.0 (SPSS, Inc.; Chicago, IL). Two separate dependent t-tests were used to assess differences between dominant and non-dominant legs for both CAR and Torque. A 2 x 2 ANOVA was performed to assess differences in inter-limb deficits on two between (sexes) and two within (testing methods), then a Tukey’s post-hoc test was applied to identify the significant relationships between variables. Pearson Product Moment Correlation Coefficient (PMCC) was also performed to identify the correlation between two testing methods (isokinetic torque and CAR). A statistical significance was determined a priori at \(p \leq 0.05\).
Chapter 4

Results

Inter-limb Deficits between Testing Method and Sex

No differences in inter-limb deficits were found between sexes ($F_{1, 23} = .001; p = .977$). There was no significant sex by testing method interaction ($F_{1, 23} = .003; p = .955$). We did find a significant difference in inter-limb deficits between testing methods ($F_{1, 23} = 4.140; p = .05$, Table 5) with isokinetic torque having greater deficits compared to CAR (Table 2). No significant difference was found between the dominant and non-dominant legs for both the muscle activation test ($t_{24} = -.67; p = .51$) and muscle strength test ($t_{24} = .79; p = .44$; Table 6 & Table 7). There was no significant correlation between inter-limb difference scores for muscle activation and muscle strength test ($r = -.056, p = .79$, Figure 1).
Chapter 5

Discussion

Previous literature has been conducted either CAR or isokinetic strength testing to evaluate quadriceps deficits with patients who had knee joint injuries. Although both measurements were used to identify quadriceps deficits, different aspects of muscle function were evaluated. In this study, CAR and isokinetic strength were compared between dominant and non-dominant legs of healthy subjects, as well as the relationship between these measures.

It was hypothesized that inter-limb differences would not be affected by testing methods or sexes. CAR inter-limb deficits were not different between males (5.034 ± 5.85) and females (4.98 ± 4.19, Table 3). Similarly, torque inter-limb deficits for males (12.63 ± 7.66) and females (12.96 ± 23.18, Table 4) were not significantly different. Conversely, inter-limb isokinetic torque deficits were found to be significantly greater than inter-limb deficits for CAR, suggesting that these two testing methods are measuring two separate neuromuscular phenomena (Table 2 & Table 5).

Another hypothesis was that leg dominance will not significantly affect both CAR and isokinetic muscle strength. Data showed that dominant leg CAR (0.94 ± 0.053) and non-
dominant leg CAR (.95±.058) were not significantly different (p=.51), and dominant leg 
torque (2.16 ±.62) and non-dominant leg torque (2.10 ± .45) were also not significantly 
different (p=.44). Therefore, we also accepted this hypothesis.

The last hypothesis was that inter-limb differences in CAR would not be correlated with isokinetic strength. As we found that inter-limb isokinetic torque deficit were significantly higher than inter-limb CAR deficit, this result supported this hypothesis. Furthermore, Pearson Product Moment Correlation Coefficient (PMCC) revealed that there was no significant correlation (r = -.06, p=.79) between two testing methods, which supported our hypothesis.

**Central Activation Ratio (CAR) testing Vs. Isokinetic Muscle Strength testing**

**CAR Testing**

Most of previous literatures\(^{15,21,30}\) used CAR to evaluate volitional muscle activation with unilaterally injured subjects, and most of their results showed that there was significant difference between inter-limbs even subjects spent several months for knee rehabilitation. Those studies concluded that AMI was the key factor to influence of quadriceps deficit. In this study, we compared inter-limbs with healthy subjects, and there was no significant difference. Although the dominant leg may have more forceful muscle contraction than non-dominant leg, the quadriceps deficit was not high enough to prove inter-limb difference with healthy subjects. However, the standard deviations in the dominant leg were lower than non-dominant leg which suggests that quadriceps activation variability may be less in the dominant limb.
Muscle contraction requires both central and peripheral nerve activation processing. Every system of the human body is controlled by the central nervous system (CNS) which consists of the brain and spinal cord. Afferent nerves send input information to the CNS, and the CNS responds with output information by motor efferent nerves. Many of the body’s control system are affected by reflexes, and these reflexes occur over reflex arcs. Reflex arc is consisted of receptor, sensory neuron, interneuron, motor neuron and effector. When receptors (especially mechanoreceptors) receive stimuli, it transfers the afferent information to spinal cord by sensory fiber. Sensory fibers are indirectly connected to motor fibers via interneuron which located at the dorsal horn of the spinal cord. As the result of joint injury, improper afferent information sends to CNS, and its reflexive motor efferent nerve decreases the ability to recruit proper amount of motor neurons within motor neuron pool (MN). Therefore, it also decreases the force to contract quadriceps muscle group. Kent-Braun and Le Blänc stated that at this point, CAR test evaluates motor neuron recruitment and muscle fibers firing frequency. Decrease in CAR means that it may have central activation failure, and it may also contribute significantly to muscle weakness.

**Isokinetic Muscle Strength Testing**

Isokinetic muscle strength testing evaluates the amount of torque generated by the target muscle or muscle group. Isokinetic machines are originally designed for research protocol, but it becomes one of the clinical tools to evaluate muscle strength in many areas because it provides an objective and standardized protocol. Compared to CAR testing, isokinetic muscle strength test cannot isolate one muscle to another for example, it can measure strength of knee extensors, but it cannot identify strength of each knee
extensors such as vastus medialis, rectus femoris, and vastus lateralis. Human body has compensatory muscle action which means if someone has soft tissue injury on vastus medialis, this person may accomplish knee extension with other knee extensors. Of course, it would be different depending on grade of injury, but it may still have underlying of muscle compensatory movement. Compared to CAR test, some of isokinetic studies could not find any significant inter-limb difference between injured and non-injured leg or between subjects after several months for participating in knee rehabilitation programs\textsuperscript{17,25,26,47}.

In this study, we used isokinetic testing to evaluate inter-limbs differences in healthy subjects. However, unlikely unilateral knee injured subjects\textsuperscript{19,27,28,29}; there was no significant difference between limb dominance. The dominant leg may produce a more forceful muscle contraction, but it did not provide significant data to distinguish this difference. However, if there is a significant difference between inter-limbs, it would mean that this subject may have significant muscle imbalance. Chaudhari and colleagues\textsuperscript{43} stated that increased shear force changed contact point on articular joint surfaces between the femur and tibia, and it decreased proteoglycan deposition because of reduced compression force. Proteoglycans comprise the crucial extracellular matrix component of cartilage; therefore decreased proteoglycans may lead to early degeneration of cartilage such as osteoarthritis (OA).

**Limb-dominance in Lower Extremities**

Compared to the upper extremity, the lower extremity may be used with more equal distribution. People can distinguish the dominant leg from the non dominant leg,
but people may equally use lower extremity during daily life such as walking, running, and climbing stairs. Like previous literature\textsuperscript{13,14,21,24,30,40,46}, if we tested unilaterally injured subjects, we also may find a significant difference between injured and non-injured side of legs. From our findings, none of testing methods revealed that there was significant difference in inter-limb deficit. Generally people do not distinguish leg dominance as long as they are not involved in some types of movements or exercises which require usage of dominant leg more than another. However, if any healthy person shows inter-limb difference during daily life, it may represent of soft tissue imbalance, and this person needs further evaluation from physician. However, if subjects are athletes who use more one side of leg than the other such as soccer player, it may show different aspect on limb-dominance.

In this study, there was a significant difference between inter-limb isokinetic torque deficit and inter-limb CAR deficit. It may mean that those two tests may have different meaning from each other. The PMCC revealed that there was no significant correlation between test methods. It describes that we could not expect similar result at one test method from another. It will be important aspect for athletic training because knee injured athlete may have higher percentage of activation according to the CAR test, but it may have lower percentage of strength according to an isokinetic muscle strength test or may not for example, then athletic trainer may determine his/her physical condition only based on one test.

\textbf{Limitations}
One of the limitations was that we addressed only one joint angle (90°). Ninety degrees may be the most stable angle for the knee joint; however, other joint angles may need to be tested to understand how activation and strength are affected between legs throughout knee range of motion. Another limitation was the psychological impact on testing especially on the CAR test. The CAR test provided a superimposed burst when subjects maximally contracted quadriceps, and in this test, it required total three trials (collected last two trials out of three). Most of subjects felt uncomfortable when receiving the superimposed burst during testing. This may have caused some of them to produce different results on each trial. The final limitation was that we only used young healthy subjects. It remains unknown how these two tests affect on older age and injured subjects.

**Recommendation for Future Research**

Since this study used healthy subjects, this study may provide normative values for future studies which could compare injured limbs and healthy limbs with young or old age. Future research could also perform a more dynamic range of motion because it remains unknown how these two testing methods would bring different or similar data at the variety of range of motion.

**Conclusion**

This study compared leg differences in CAR test and isokinetic muscle strength test with healthy subjects. From our data analysis, we did not find out any statistically significant differences between limbs for those two testing procedures. We may assume that healthy subjects may distribute an equal amount of force to use lower extremities.
during daily life. We also found out that there was no significant difference in inter-limb deficits and sex. Males may create higher force to contract muscle, but absolute value showed that there was no significant difference between sexes. We did find that inter-limb deficits were higher for isokinetic torque compared to CAR. Additional data analysis also showed that those two tests were not correlated to each other. It means that we cannot expect the deficits in quadriceps activation to be similar to deficits in strength.
Tables

Table 1. Subject Demographics Means (Standard Deviations)

<table>
<thead>
<tr>
<th>Subjects (N=25)</th>
<th>Males = 11, Females = 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>25.08 ± 4.67</td>
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<tr>
<td>Mass (Kg)</td>
<td>67.04 ± 10.67</td>
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<tr>
<td>Height (cm)</td>
<td>172.89 ± 7.74</td>
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Table 2: Mean and Standard Deviation for Muscle Activation (CAR) Absolute Deficit and Muscle Strength (Torque) Absolute Deficit

<table>
<thead>
<tr>
<th>Test</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Deficit for CAR</td>
<td>4.97</td>
<td>4.87</td>
</tr>
<tr>
<td>Absolute Deficit for Torque</td>
<td>12.82</td>
<td>17.76</td>
</tr>
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</table>

Table 3 Mean and Standard Deviation for Muscle Activation (CAR) Deficit

<table>
<thead>
<tr>
<th>Gender</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
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<tr>
<td>Male</td>
<td>5.03</td>
<td>5.85</td>
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<tr>
<td>Female</td>
<td>4.92</td>
<td>4.18</td>
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Table 4: Mean and Standard Deviation for Muscle Strength (Torque) Deficit

<table>
<thead>
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<th>Gender</th>
<th>Mean (Nm/Kg)</th>
<th>Standard Deviation (Nm/Kg)</th>
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<tbody>
<tr>
<td>Male</td>
<td>12.63</td>
<td>7.66</td>
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<tr>
<td>Female</td>
<td>12.96</td>
<td>23.18</td>
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Table 5. Statistical Summary

<table>
<thead>
<tr>
<th>Interaction</th>
<th>F_{1,23}</th>
<th>p-value</th>
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<tbody>
<tr>
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<td>.05</td>
</tr>
<tr>
<td>Gender</td>
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<td>.98</td>
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<tr>
<td>Test x Gender</td>
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<td>.96</td>
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</tbody>
</table>

Table 6. Mean and Standard Deviation for Dominant leg and Non-Dominant leg on Muscle Activation test and Isokinetic Muscle Strength test

<table>
<thead>
<tr>
<th>Test</th>
<th>Leg</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAR</td>
<td>Dominant</td>
<td>.94</td>
<td>.05</td>
</tr>
<tr>
<td></td>
<td>Non-dominant</td>
<td>.95</td>
<td>.06</td>
</tr>
<tr>
<td>Torque</td>
<td>Dominant</td>
<td>2.16</td>
<td>.62</td>
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<tr>
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<td>Non-dominant</td>
<td>2.10</td>
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Table 7. Summary of Paired T-test

<table>
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<th>t_{24}</th>
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<td>Non-dominant</td>
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<tr>
<td>Torque</td>
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Figure 1. Biodex system 2

Figure 2. Grass Stimulator (S88)
Figure 3. Isokinetic Testing

Figure 4. Application of Electrodes for CAR Testing
Figure 5. Correlation between CAR test and Isokinetic Muscle Strength test
References


