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# Comparison of Anterior Cruciate Ligament Reconstruction Using Quadriceps Autograft Versus Bone-Patellar Tendon-Bone Autograft on Neuromuscular Activity of the Quadriceps and Gait Biomechanics

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UNIVERSITY OF MIAMI

# COMPARISON OF ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION USING QUADRICEPS AUTOGRAFT VERSUS BONE-PATELLAR TENDON-BONE AUTOGRAFT ON NEUROMUSCULAR ACTIVITY OF THE QUADRICEPS AND GAIT BIOMECHANICS

By

Michael Isaac Letter

A DISSERTATION

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Comparison of Anterior Cruciate Ligament Reconstruction using Quadriceps Autograft versus Bone-Patellar Tendon-Bone Autograft on Neuromuscular Activity of the Quadriceps and Gait Biomechanics

Abstract of a dissertation at the University of Miami.

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Quadriceps tendon autografts (QT) are increasingly popular as a primary graft choice for anterior cruciate ligament reconstruction (ACLR); yet no study has compared QT and bone-patellar tendon-bone autograft (BTB) superficial quadriceps neuromuscular activity levels during gait and isometric strength testing. The objective of this study was to determine if harvesting the central portion of the QT will alter gait biomechanics and RF firing patterns during gait and an isometric maximum voluntary contraction (MVC). Thirty-four subjects (18-40 y), who underwent ACLR using BTB (n=17) or QT (n=17) at a single institution, and seventeen healthy age-matched controls (C) participated. Subjects had no neuromuscular pathology or prior surgery on either lower extremity, were at least one-year post-ACLR, and were cleared for full activity by their treating surgeons. Post-operative rehabilitation protocols were the same for all subjects. Synchronized electromyography (EMG) and isometric torque data were collected on ACLR subjects in seated position with hips flexed to 90° and knee at 60° flexion. Subjects were asked to extend their knees as quickly as possible and perform an MVC for 3s. A practice trial and three test trials were completed with 30s rest intervals. Synchronized EMG was also

collected in conjunction with sagittal kinetic/kinematic data as subjects walked at their self-selected cadence along a 20-foot course containing two offset force plates. Three gait trials were performed with one complete gait cycle identified for analysis during each trial. Mixed 2 condition x 2 limb (affected versus unaffected) ANOVAs were used to examine differences in average and peak torque values during isometric testing, joint angles, joint moments and ground reaction forces (GRF) during gait testing. RF, VM, and VL EMG amplitudes were assessed during gait and RF/VL and RF/VM EMG ratios during both isometric and gait testing. Lysholm and IKDC scores were compared between groups using paired t-tests. Significantly lower values were seen for the affected compared to the unaffected extremity for peak ($p=.008$; $\eta^2=.201$) and average torque ($p<.0001$; $\eta^2=.321$) with no significant differences between groups. Additionally, no significant differences in RF/VL or RF/VM ratios were seen between affected and unaffected limbs or groups during gait or MVC. In the QT group, maximum knee angle was significantly less than that of the BTB group in the unaffected extremity (MD=-15.00, $p=.002$). In summary, at greater than one year following ACLR, QT and BTB autographs showed similar isometric strength deficits; however, no differences in quadriceps muscles EMG ratios were seen between the groups during isometric testing or gait, although kinematic asymmetries were observed in the QT group. Additional research is warranted to further investigate the longitudinal effect of kinetic and kinematic alterations on knee function and joint health after QT ACLR. Our results provide additional evidence for the QT as a choice for ACLR, as this graft harvest does not adversely affect quadriceps firing patterns.

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# CHAPTER 1: INTRODUCTION

The use of the quadriceps tendon for anterior cruciate ligament reconstruction (ACLR) has been discussed since 1979.[7] Initial autologous quadriceps tendon harvest techniques involved a patellar bone block harvest (QTB), similar to that of a bone-patellar tendon-bone autograft (BTB).[31] Advances in technology and instrumentation have given physicians and patients additional graft options. In 1999, Fulkerson[18] discussed harvesting autologous quadriceps tendon without incorporating the patellar bone block (QT). Since that time, the use of QT for ACLR has increased in prevalence. It was reported in 2010 that only 1% of surgeons were performing QT ACLR[43]; however, in 2014, an international poll involving 20 countries found that 11% of surgeons were now performing QT ACLR.[33]

The literature has shown that patients who have undergone ACLR with QT have experienced good to excellent outcomes.[25,26,34,40] Nevertheless, chronic quadriceps weakness has been commonly reported following ACL injuries[20,21,30,31] and deficits in quadriceps strength are known to persist despite ACLR, months of advanced outpatient physical therapy, and home exercise.[8,14,41,44] Dreschler[17] evaluated isometric quadriceps torque of the injured and uninjured legs of 31 subjects following BTB ACLR and reported that at three months post-surgery, 86% of subjects had significant muscle weakness. Similarly, Suter[41] observed decreased knee extensor strength at an average of 22 months following BTB ACLR. Chen[8] found that between four and seven years post-surgery, subjects who underwent ACLR using QT with bone block (QTB) regained 91.7% of their extension strength in the surgical limb when compared to the contralateral side. Similarly, Lee[28] reported that 85.1% of extension strength was regained at a minimum of 2 years following QTB ALCR. In a study comparing BTB and QTB grafts in age and gender matched patients, Han[22] found no significant difference between groups in extensor strength at two years after surgery. In 2015, Slone[40] conducted a comprehensive and systematic review of the current literature assessing a variety of outcomes. He concluded that the "use of the quadriceps tendon autograft for ACL reconstruction is supported by current literature; it is a safe, reproducible, and versatile graft". Taken together, these results suggest that the QT is as effective, if not more effective, at restoring quadriceps function as BTB.

Physiological advantages of QT versus BTB include, greater cross-sectional area (1.8x thicker) with 20% more collagen[23], a stronger extensor mechanism[2] and decreased comorbidities (patella fracture, anterior knee pain). Contraindications for using QT include prior quadriceps rupture and chronic quadriceps tendinopathy[10]. Traditionally, the quadriceps tendon distal attachment has been described as trilaminar, with a deep vastus intermedius (VI) layer, an intermediate adipose layer where the vastus medialis (VM) and vastus lateralis (VL) insert, and a superficial rectus femoris (RF) layer. The average QT patellar insertion is 27 mm wide and 16 ± 2 mm deep in males, and 18 ± 2 mm deep in females. The RF and VI are joined to form the common tendon 6 cm from the superior pole of the patella, with an average thickness of 8 mm. Deangelis[13] described harvesting a QT graft 6 to 7mm in depth, 9 to 10 mm in width, and 7 to 8 mm in length without violating the supra-patellar pouch.

Electromyographic (EMG) activity of the superficial quadriceps has been reported at different time intervals following ACLR. Using fine-wire electrodes, Ciccotti[9] examined

EMG activity levels of the VM, VL, RF, semimembranosus, long head of biceps femoris, tibialis anterior, gastrocnemius and soleus, following 8-12 months of formal physical therapy. They evaluated 22 normal knees, eight rehabilitated ACL-deficient knees, and 12 reconstructed (BTB) knees during performance of seven functional activities and found that EMG activities of the VL, RF, and VM did not differ significantly between subjects with reconstructed knees and those with normal knees. Similarly, Knoll[27] found that EMG patterns of ACLR subjects were close to control values at 8 months post-operative. In contrast, Pfeifer[37] evaluated ACLR subjects as they performed three dynamic tests: stair descending, one legged drop jump, and one-legged cyclic hop. They found significant task dependent neuromuscular performance differences in the RF, VM, VL, biceps femoris and gastrocnemius at 10-16 months in the surgical extremity when compared to the contralateral extremity.

Previous studies have provided longitudinal kinetic and kinematic data following BTB ACLR. Devita[15] observed abnormal gait patterns three weeks following ACLR; but found that gait began to normalize at five weeks following reconstruction. Ten months following ACLR, Timoney[42] found a significant reduction in external flexion moment at midstance, and a reduction in peak knee flexion when comparing BTB subjects to healthy controls. Bulgheroni[4] found kinematic, kinetic and EMG values returning to normal 17±5 months post-operatively, suggesting that ACLR subjects had regained normal gait values. In 2016, Hart[24] conducted a meta-analysis and systematic review on knee kinematics and joint moments following ALCR using BTB, Achilles allograft, and hamstring autograft at greater than six months after surgery. They found greater knee flexion angles and moments in the ACLR groups compared to healthy controls. They believed this may have been caused by muscle inhibition, joint swelling, and post-operative pain. Lower knee flexion moments and lower peak flexion angles were seen at six to twelve months and were theorized to be secondary to altered hamstring or quadriceps activation patterns. Although previous studies have examined kinetics and kinematics in BTB patients following ACLR, to our knowledge, no study has compared gait kinetics/kinematics and comparative levels of neuromuscular activity among the superficial quadriceps muscles of the injured versus uninjured limbs of individuals that have undergone ACLR using QT and BTB. Due to the superficial position of the RF aponeurosis on the quadriceps tendon and its direct linear pull on the patella, we theorized that QT graft harvest would affect quadriceps firing patterns either by increasing RF use due to the need to compensate for reduced biomechanical efficiency or reducing activity due to the compensation by the VL and VM. Persistent quadriceps weakness has been associated with decreased knee flexion angles and decreased internal knee extensor moments up to one year post-ACLR.[5]

Due to the superficial position of the RF aponeurosis on the quadriceps tendon and its direct linear pull on the patella, we theorized that QT graft harvest would affect quadriceps firing patterns either by increasing RF use due to the need to compensate for reduced biomechanical efficiency or reducing activity due to compensation by the VL and VM. Therefore, we used surface electromyography (sEMG), isometric dynamometry and gait analysis to assess RF, VM and VL activity, torque production, and kinetics/kinematics, respectively, in QT and BTB ACLR patients at greater than one year after surgery. At this time most patients show normal EMG activity[9,27], close to normalized gait, and have returned to sport with no restrictions. Our primary hypothesis was that both groups would show decreased isometric torque values for the affected leg, and the ratios of the RF to VM and VL would be lower in QT ACLR patients due to graft harvest of the quadriceps tendon. We further hypothesized that decreased knee flexion angles and decreased internal knee extensor moments would exist secondary to quadriceps weakness and alterations in the superficial quadriceps firing patterns.

# CHAPTER 2: METHODS

## Subjects

Thirty-four subjects who had undergone ACLR using BTB (n=17) or QT (n=17) at the same institution, and seventeen healthy controls (C), were recruited for this study. All procedures were approved by the University's Internal Review Board for the Use and Protection of Human Subjects and all subjects provided written consent. Two board certified sports medicine orthopedic surgeons performed the surgeries. One surgeon performed the majority of the QT ACLR (15/17); while the other performed the majority of the BTB ACLR (11/17). Subjects were between 18 and 40 years of age and had undergone ACLR at least one year earlier. They had no previous neuromuscular pathology or prior surgery on either lower extremity and were cleared for full activity at the time of evaluation. Potential subjects were excluded from participating if they had a BMI > 35, articular lesion(s) greater than Outerbridge grade II at time of surgery, multi-ligament knee injury, a Tegner activity score < 4, or meniscal injury that would affect post-operative weight-bearing or range of motion. Post-operative rehabilitation protocols were the same in all subjects. Anthropometric data, Lysholm Knee Scoring Scale, and International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form data were collected prior to testing. Descriptive characteristics of study participants are presented in Table 1.

## Surgical Technique and Postoperative Treatment

### *Quadriceps Tendon Autograft*

For the QT ACLR, a 3-cm longitudinal incision was made to harvest the ipsilateral quadriceps tendon. A graft, 9 to 10 mm in width, was harvested from the central-medial portion of the quadriceps tendon in the fashion described by Deangelis.[13]

*Bone-Patellar Tendon-Bone Autograft*

A longitudinal incision was made from the inferior pole of patella to the medial aspect of the tibial tubercle during the BTB harvest technique. Initially, a 10 mm central portion of the patellar tendon was delineated, then cuts were performed with an oscillating saw to obtain a 25 mm bone plug from the tibia, and a 20 mm bone plug from the patella, both 10mm in width.

Regardless of the harvesting technique, all subjects received standard post-operative rehabilitation protocols. Subjects were encouraged to initiate physical therapy within the first week of the procedure. All received no weight bearing or range of motion restrictions. Subjects were initially evaluated 7-10 days following procedure for routine follow-up and were evaluated at regular intervals.

Patients were allowed to return to sport with no restrictions once their knee was deemed stable and they had adequately recovered quadriceps strength. All patients enrolled in this study had returned to sport with no restrictions.

Testing

*Isometric and Electromyographic Testing*

A Biodex 4 isokinetic dynamometer (Biodex Corporation, Shirley, NY) and integrated EMG collection system (Biopac MP150 system, Biopac Systems, Inc., Goleta, CA) were used to assess isometric torque and quadriceps muscle activity, respectively.

*Isometric Testing.* Participants were seated on the Biodex chair and the axel of the powerhead was aligned with the subject's lateral condyle. Restraints were placed across the chest and at the waist to reduce unwanted movement. Subjects' hips and knees joints were held at 90º and 60º, respectively. Subjects were familiarized with the system prior to testing and each subject performed an active one repetition practice trial. The practice trial was followed by a minimum of three successful test trials. A successful trial was determined by an established pattern including a steep increase in torque followed by a three second plateau. Subjects' non-surgical limbs were tested first. Vocal encouragement during the testing was standardized. Subjects were asked to exert force as quickly as possible and maintain a maximal effort for 3 seconds. During all trials, subjects were allowed to track their performance on the Biodex screen, since visual feedback in conjunction with verbal encouragement has been shown to positively affect performance during strength testing.[3,6] Subjects were given a 30s recovery between trials. Isometric MVC and sEMG (RF, VM, VL) data were collected during each effort.

*Isometric Electromyography.* Prior to isometric testing subjects were prepared for sEMG data collection. A bipolar surface electrode configuration with an interelectrode distance of 1 cm was used to maximize the reception area. This interelectrode distance is effective in reducing the potential for crosstalk in most muscles.[11] The skin overlying each muscle was shaved, abraded, and cleansed with rubbing alcohol to remove dead surface tissues and oils, thereby reducing impedance at the skin-electrode interface. Disposable Ag/AgCl dual electrodes (Noraxon USA, Inc., Scottsdale, AZ) were positioned parallel to the underlying muscle fibers according to *Cram's Introduction to Surface Electromyography* recommendations.[11] Raw EMG and force data were recorded simultaneously using the

Biopac MP150 system (Biopac Systems, Inc., Goleta, CA). The Biopac 150 system has an input impedance of 1.0 MΩ and common mode rejection ratio (CMRR) of 110 dB at 50/60HZ. The gain was set at 1,000 with band pass filtering set between 20 and 450 Hz. Signals were sampled at a frequency of 1000 Hz, digitized using a 16-bit A/D converter, and stored on a laptop laboratory computer. Recorded EMG signals from each muscle were analyzed using the Biopac 150 system software. The mean rmsEMG values (RF, VM, VL) were calculated for each effort and ratios were computed between the RF and the vasti muscles.

*Kinematic/kinetic/Electromyography* A bipolar surface electrode configuration with an interelectrode distance of 1 cm was used to maximize the reception area. This interelectrode distance is effective in reducing the potential for crosstalk in most muscles.[11] The skin overlying each muscle was shaved, abraded, and cleansed with rubbing alcohol to remove dead surface tissues and oils, thereby reducing impedance at the skin-electrode interface. Trigno electrodes (Trigno Wireless System, Delsys Inc., Natick, MA) were positioned parallel to the underlying muscle fibers according to *Cram's Introduction to Surface Electromyography* recommendations.[11] Raw EMG, kinetic and kinematic data were recorded simultaneously using the using the wireless telemetry system. The gain was set at 2,000 with band pass filtering set between 20 and 450 Hz. Signals were sampled at a frequency of 2000 Hz, digitized using a 16-bit A/D converter and stored on a laptop laboratory computer. Recorded EMG signals from each muscle were analyzed using a custom-built software program (LabView; National Instruments Corporation, Austin, TX, USA) written to quantify the rmsEMG.

Prior to attending the testing session subjects were instructed to wear spandex shorts to allow optimal skeletal mapping during gait trials. Anthropometric measurements including leg length, knee width, and ankle width were then recorded. Leg length was measured as the linear distance between the anterior superior iliac spine (ASIS) and the medial malleolus. Knee width was the distance from the medial epicondyle to lateral condyle, and ankle width was measured from the medial malleolus to lateral malleolus. These measures were made using a spring caliper. Bilateral quadriceps circumference was recorded using a spring-loaded tape measure to reduce tissue compression. Sixteen passive reflective markers were then positioned over designated anatomical points of each lower extremity, trunk and pelvis according to the model described by Davis et al. (Figure 1).[12] Subjects then stood in a T-pose for one second to facilitate the skeletal tracking. Subjects were then familiarized with the testing protocol and practiced walking before data collection began.

*<Place Figure 1 about here>*

During testing, each subject was asked to perform at least three gait trials, ambulating at their normal self-selected cadence. A 20-foot course containing two offset force plates was used to allow ground reaction forces (GRF) to be collected during normal cadence. One complete gait cycle was identified in each trial. Gait trials were recorded using an eight-camera BTS opto-electronic motion capture system (SMART-DX 7000, BTS Bioengineering, Milano, Italy) at a sampling rate of 100 Hz. GRF data were collected using two force plates (Type 9286AA; Kistler Instrument AG, Winterhur, Switzerland), and EMG data was gathered using the Delsys EMG telemetry system (Trigno Wireless System, Delsys Inc., Natick, MA). All systems were synchronized to allow time-matched data collection. BTS data were processed using Vicon Nexus software (VICON

Motion Systems, Inc., Oxford, UK). The gait cycle, from initial contact (IC) through toe-off (TO), was defined using the method of Geerse et al.[19], where the IC and TO are defined as the maxima and minima of the toe trajectory curve with respect to the patient's center of mass in the anterior and posterior directions, respectively. The initiation of the rise phases was defined as estimated event time of the first frame after which the marker had continuous vertical and progressive motion.

**Data Analyses:**

**Isometric:** Peak torque (PT) and average torque (AT) were exported from a Biodex 4 isokinetic dynamometer to the Biopac 150 software.

**Isometric EMG**: Raw sEMG data were windowed at 1-2 seconds for each trial. Mean values for the root mean square of the EMG signal (rmsEMG) were calculated using the Biopac 150 system. Ratios were calculated using rmsEMG values of the RF and VM (RF/VM) and RF and VL (RF/VL) for the affected and unaffected knees and comparing them to determine if the RF contribution was affected by the surgical procedure. Further, these ratios were compared for the affected knees of QT and BTB ACLR patients.

**Kinematic/kinetic:** Hip and knee kinematics and kinetics were calculated for each trial. Kinematic sagittal variables included: hip and knee joint angles at initial contact (IC) and toe-off (TO) for the affected and unaffected legs, and maximal hip and knee joint angles among the steps. Kinetic variables included: hip and knee moments, and ground reaction forces (GRF) for both legs. The data were post-processed and analyzed using Vicon Nexus 2.2.3 software (Vicon Motion Systems Inc., Oxford, UK).

**Kinematic/Kinetic EMG:** Raw sEMG data were collected using the Delsys EMG telemetry system throughout each phase of the gait cycle (stance/swing). BTS data were processed using Vicon Nexus software (VICON Motion Systems, Inc., Oxford, UK. Mean values for rmsEMG were calculated, as were ratios using the rmsEMG values of the RF with the VM (RF/VM) and VL (RF/VL) All data were collected for the affected and unaffected extremity and compared to determine if the RF contribution was affected by the surgical procedure. Further, these ratios were compared for all groups (QT, BTB, C).

**Statistical Analyses:**

**Sample size calculations:**

A previous investigation involving 20 participants (10 BTB, 10 C) found mean external flexion moment at midstance in the surgical limb of 2.02% (SD 1.14), and in the uninjured leg of 3.10% (SD 1.35).[42] Using G*Power (version 3.1.9.2), we calculated an effect size of d=.866 utilizing these results, a 3 x 2 repeated measures ANOVA model with an alpha = 0.05, 1-beta = 0.95, and an effect size d=0.866, we calculated a required sample size of 24.

**Isometric torque and EMG:** A 2 (affected and unaffected limb) x 2 (group) repeated measures ANOVA, using the averages of the peak and average torque scores across the three repetitions was performed to determine if significant differences existed in torque between the affected and unaffected legs and the two graft conditions. A 3 (repetition) x 2 (affected and unaffected limb) x 2 (group) repeated measures ANOVA was used to evaluate differences in quadriceps EMG ratios existed between the affected and unaffected limbs or between the affected limbs of the QT and BTB groups. When significant main effects or interactions were observed LSD post hoc analyses were used to determine the source.

**Kinematics, Kinetics and EMG:** A 2 (affected and unaffected limb) x 3 (group) repeated measures ANOVA, using the averages means and standard deviations calculated for joint angles, moments and GRF data across the three gait cycles. In the case of a significant main effect or interaction, the source of that difference was determined using LSD post hoc analysis.

The impact of group and affected to unaffected side on rmsEMG of the RF, VM and VL, and RF/VL and RF/VM ratios were examined during the stance and swing phases of the gait cycle were analyzed using multiple 2 (affected and unaffected limbs) x 2 mixed (phase) analyses of variance (ANOVA). Once again LSD post hoc analyses were used to determine the source.

Paired T-tests were used to assess differences in Lysholm and IKDC scores. The alpha level for significance in all tests was set *a priori* at 0.05.

All analyses were performed using SPSS (version 17.0; SPSS, Chicago, IL).

# CHAPTER 3: RESULTS

The flow of subjects through the study is presented in Figure 2. All subjects completed every aspect of the study.

*<Place Figure 2 about here>*

## Isometric Torque

Data from thirty-four subjects, who had ACLR surgery at least one year prior to recruitment, and seventeen healthy control subjects, were included in our analysis. Baseline characteristics of these subjects are presented in Table 1.

*<Place Table 1 about here>*

For isometric AT, significant differences were found between the affected and unaffected legs for the entire sample ($p=.008$; $\eta^2=.201$); however, no significant main effect for graft ($p=.728$, $\eta^2=.004$) or graft x leg interaction ($p=.489$; $\eta^2=.015$) were detected (Table 2). This pattern was also seen for PT, where a significant main effect was seen for limb ($p<.0001$; $\eta^2=.321$), while no main effect for graft ($p=.618$; $\eta^2=.008$) or graft x leg interaction ($p=.504$; $\eta^2=.014$) was detected (Table 2).

*<Place Table 2 about here>*

## EMG during Isometric Testing

The analysis of the RF/VM ratio produced no significant differences by repetition ($p=.759$; $\eta^2=.009$), affected versus unaffected legs ($p=.196$; $\eta^2=.052$) or between grafts ($p=.740$; $\eta^2=.003$), nor were there any significant interactions. Similarly, no significant differences were found for the RF/VL ratio among repetitions ($p=.232$; $\eta^2=.045$), between affected and unaffected legs (p=.196; $\eta^2$=.005) or between grafts (p=.373; $\eta^2$=.025); and once again there were no significant interaction (Table 3).

*<Place Table 3 about here>*

**Kinematics and Kinetics**

Hip Kinematics and Kinetics

For maximal hip angle throughout the gait cycle there were no significant affected to unaffected side or group main effects. There was also no significant affected to unaffected side by group interaction. No significant affected to unaffected side or group main effects were seen at the hip during IC, nor was there a significant affected to unaffected side by group interaction. The results for TO mirrored those for IC at the hip; with no significant main effects or interaction.

For maximum hip moment there were no significant main effects for group or affected to unaffected side. Additionally, there was no significant group by affected to unaffected side interaction.

For maximum angle at the knee, there was a significant affected to unaffected side by group interaction ($p$=.013, $\eta^2$=.186) (Figure 3). Post hoc analysis revealed maximum knee angle on the affected side in the QT group was significantly less than in healthy controls (MD=-10.4, $p$=.021); while on the unaffected side, the QT group maximum knee angle was significantly less than that of the BTB group (MD=-15.00, $p$=.002) and the healthy controls (MD=-15.86, $p$<.001). When examining difference between the affected and unaffected legs for each group, a significantly greater knee angle was seen for the affected versus the unaffected side of the QT group (MD=5.44, $p$=.005). In contrast, pairwise comparisons revealed no significant differences between the affected and unaffected sides for the BTB group or controls who had not undergone ACLR.

*<Place Figure 3 about here>*

For knee joint angle at IC, no significant main effects were found for group; however, a significant main effect was seen for the affected versus unaffected extremity ($p$ = 0.015, $\eta^2$ =.13). Post-hoc analysis indicated at IC the angle for the unaffected leg was lower than that for the affected leg (MD=-2.37, $p$=.015). For knee angle at TO, once again there was a significant main effect for unaffected versus affected side ($p$ = 0.05, $\eta^2$=.084). Pairwise comparisons revealed a significantly lower knee angle at TO for the unaffected side (MD=-1.82, $p$=.05) (Figure 4).

*<Place Figure 4 about here>*

For maximum knee moment there were no significant main effects for group or affected to unaffected side. Additionally, there was no significant group by affected to unaffected side interaction.

GRF produced a significant main affect for affected to unaffected side alone ($p$=.05, $\eta^2$= .088) (Figure 5). Pairwise comparisons revealed a significantly higher GRF for the unaffected side (MD=1.52 Nm, p=.05).

*<Place Figure 5 about here>*

**EMG Stance**

No significant main effect was observed for RF or VL by group or affected to unaffected side. Additionally, there was no significant interaction. VM results indicated a significant main effect for group ($p$=0.015, $\eta^2$ =.171). Post-hoc analysis showed significantly greater VM activity for the control group over the QT group (MD=0.01, $p$=.017). No significant main effects or interaction was seen for the RF/VL or RF/VM ratios during the stance phase (Table 4).

*<Place Table 4 about here>*

**EMG Swing**

No significant main effects were observed for group or affected and unaffected side for the RF, VL or VM (Table 5). No significant main effects or interactions were seen for the RF/VL ration. However, a significant main effect was observed by group for the RF/VM activation ratio ($p$=0.38, $\eta^2$=.141). Post-hoc analysis revealed that the QT group's ratio of 1.36 was significantly higher than that of the control group at .987 ($p$=.043).

*<Place Table 5 about here>*

Lysholm knee scoring scale values were lower in patients' that underwent QT than BTB and this difference approached significance ($M_{diff}$ = -11.98, $p$=.055). There was no significant difference in IKDC scores between groups.

# CHAPTER 4: DISCUSSION

## Isometric Performance and EMG

To our knowledge, no studies have compared EMG data of the superficial quadriceps of QT and BTB patients during maximal isometric testing or gait. Our results support the use of the QT autograft, as it does not affect RF activity levels or isometric torque production relative to BTB. We chose to evaluate subjects at greater than one year after surgery, as most patients show normal EMG activity[9] and have returned to sport with no restrictions at that time.

Our findings, showing an 11.6% difference in isometric PT and 18.4% in isometric AT, are consistent with previous studies showing diminished quadriceps strength beyond the standard rehabilitation periods.[18,20,28,29] In a group of subjects 4-7 years after QTB ACLR, Chen[8] reported an average Lysholm score of 93.0±7.9 and the recovery of 91.7% of peak torque in the surgical extremity when compared to unaffected limb. Given the substantially longer time following surgery in their group, these results were comparative to the 82.12 Lysholm score and 88.4% peak torque recovery score seen in our patients after an average of 24.9±13.5 months post-surgery. Similarly, a study by Lee[28] assessed 247 patients at an average of 44±15.5 months following QTB ACLR. They reported a 79% and 81.9% recovery in peak extension torque at 60°/s and 180°/s at one year, 81.8% and 88.4% after two years, and 85.1% and 91.2% after three years. The torque values at one and two years are comparative to the 88.4% and 81.6% deficits in PT and AT seen during isometric leg extension in our subjects. Their average Lysholm score of 90 and IKDC score, reported as ranging from grade A to grade B, also compared well to our

Subject's 82.12 Lysholm and 71.7 IKDC scores given that their patients' time of assessment ranged from 25 to 87 months post-surgery.

In a study comparing results of QTB ACLR and BTB ACLR, Han[22] reported results similar to those in our study. In 144 predominantly male patients assessed 42.1±25 months and 39.7±16.5 months after BTB and QTB, respectively, they found no statistical differences between IKDC scores or Lysholm scores between the two autografts (BTB = 92.8; QTB = 91.5), reflecting our findings. They also reported isokinetic torque ratios at 60º/s (BTB = .74±.20; QTB = .78±.13) and 180º/s (BTB = .76±.22; QTB = .82±.11) similar to those seen for isometric torque in our study at 1 year. The same pattern was reported at 2 years for isokinetic torque at 60º/s (BTB = .78±.26; QTB = .82±.15) and 180º/s (BTB = .80±.23; QTB = .89±.08).

The QT ACLR has also been compared to other autografts. During a controlled randomized trial Martin-Alquacil et al.[32] compared patterns of recovery for strength and function at 12 months in 19 patients who received QT autografts and 18 patients who received hamstring tendon autografts (HT). They reported significantly higher hamstrings to quadriceps (H/Q) ratios at 12 months for the QT versus the HT during isokinetic testing at 60, 180, and 300º/s; however, there were no significant differences in Tegner, Lysholm or Cincinnati Knee Rating scores between groups. Although leg extension isokinetic torque was lower at all testing speeds for the QT graft, these researchers argued for its superiority due to a lower H/Q ratio, noting that since this ratio would be beneficial in maintaining hamstrings' integrity during valgus pivoting activities, which could provide greater protection for the knee.

Deangelis[13] described harvesting a QT graft 6 to 7 mm in depth, 9 to 10 mm in width, and 7 to 8 cm in length without violating the supra-patellar pouch. However, due to the superficial position of the RF aponeurosis on the quadriceps tendon and the direct linear pull of this muscle on the patella, we theorized that QT graft harvest would affect quadriceps firing patterns either by increasing RF use due to the need to compensate for reduced biomechanical efficiency or reduced activity due to the compensation by the VL and VM. Our results showing no significant differences in EMG ratios between the superficial quadriceps between QT and BTB groups in the affected extremity do not support this hypothesis. Possibly, the graft harvest size was not large enough to affect the mechanical pull of the RF or require compensatory firing of the vasti muscles.

Results of our isometric testing support previous studies which investigated potential neuromuscular alterations following ACLR. Knoll[27] found no significant EMG differences during treadmill walking at 3.0 km/h in ACLR subjects compared to healthy controls 8 months following BTB surgery. Bulgheroni[4] examined EMG activities of the RF, VL, biceps femoris and semitendinosus in 15 subjects 17±5 months following BTB surgery and reported no significant difference in EMG patterns of the VL or RF between ACLR patients and controls during gait. Additionally, Cicotti[9] found EMG activities of the VL, RF, and VM 8-12 months following ACLR to be very similar to those of healthy controls.

**Kinematics/Kinetics**

A number of studies have focused on evaluation of kinematic and kinetic changes in the affected extremity following ACLR, while ignoring potentially relevant findings in the unaffected extremity. Although patients that undergo QT ACLR generally restore acceptable muscle strength and stability[25,34,40], the function during gait or sport is still not well documented in both affected and unaffected extremities. Di Stasi[16] conducted a study involving twenty-one ACL deficient athletes and 10 healthy subjects who performed the same levels of activity. She qualitatively compared limb behaviors to determine clinically meaningful asymmetries. Subjects underwent a ten-session physical therapist guided neuromuscular perturbation training program designed to improve the dynamic stability of the knee through timely co-activation of the surrounding musculature. She determined minimal clinically important difference (MCID) values for the sagittal plane hip and knee kinetics and kinematics. MCID values were determined to be 3 degrees for hip and knee kinematics in the sagittal plane during weight acceptance, and .06 Nm/Kg-m and .04 Nm/Kg-m for hip and knee kinetics respectively.

In our study, the QT maximum knee angle on the affected side was significantly less than for the C group (MD=-10.4, p=.021) and on the unaffected side was significantly less than the BTB group (MD=-15.0, p=.002) and the C group (MD=15.86, p<.001). Both values were greater than the MCID threshold and are therefore considered clinically relevant.

Our finding that the maximum knee angle of the QT group for the affected extremity was less than that for healthy controls is comparable to the findings reported in three systematic reviews. In their review of 27 articles published from 1970 through 2013, Slater et al.[39], reported that peak knee-flexion angle and external knee-extensor moment were smaller in their ACL repair group than in controls at 10 to 40 months post-surgery. The results of a meta-analysis and systematic review of 34 studies conducted by Hart[24], reported that individuals may walk with lower knee flexion angles and moments compared to healthy controls. Our finding of greater knee angles for the affected versus unaffected leg was not fully supported by their analysis of patients at greater than 6 months post-surgery; however, they did note that these greater knee angles and moments may have been related to the inability of the quadriceps muscles of the operated knee to be effectively activated so that they might resist the external flexor moment. The similar quadriceps rmsEMG and RF/vasti ratios between legs, and between ACLR subjects and C, may indicate greater recovery levels in our patients than in their sample. This is further supported by the lack of significant differences between the affected and unaffected legs, and compared to controls, in knee moment and ground reaction forces seen in our subjects. Further, our significant findings, within in the QT group, of increased peak flexion angles in the affected extremity may be secondary to the minimally invasive nature of the QT graft harvest.

We also observed significantly lower knee joint angles in the unaffected leg at IC and TO compared to the affected extremity in all groups; however, our significant values at IC and TO did not reach the MCID threshold of clinical significance. Additionally, significantly higher GRFs for the unaffected side were observed. The lower joint angles in the unaffected extremity seen during IC and TO is supported by the hypothesis that a unilateral ACL injury can provoke a bilateral kinetic response[24], as compensatory adaptations of the contralateral extremity attune deficits in the surgical limb[16]. Roewer[38] evaluated quadriceps strength and gait analysis at 6 months and 2 years following ACLR. He found that the altered moments evident at 6 months following ACLR became more symmetrical secondary to alterations in the unaffected extremity over time, rather than changes in the reconstructed extremity.

Asymmetrical kinematic findings have been linked to quadriceps weakness.[35] Palmieri-Smith evaluated seventy-three ACLR patients that were cleared for return to play. Isokinetic quadriceps strength was evaluated in both knees and biomechanical data were collected during a single landing task. They concluded that subjects that had lower quadriceps strength showed greater movement asymmetries at the knee in the sagittal plane.[35] Our isometric strength results indicate that we may reject the hypothesis that the current asymmetric kinematic findings are secondary to quadriceps weakness as we found no difference in BTB and QT groups in the affected extremity (AT, PT). Additionally, the asymmetry in GRF was a main effect, and therefore not attributable to either ACLR group.

**Kinematics/Kinetics EMG**

Though we did not observe alterations in neuromuscular activity during gait testing between BTB and QT groups in the affected leg, activity levels did vary slightly from those of C subjects. During stance phase, the C group showed significantly greater VM activity over the QT group, and during the swing phase RF/VM ratio was significantly higher in the QT group (1.36) compared to the C group (.987). It is plausible that during swing phase, the increased RF activity in the QT group could be secondary to graft harvest with associated potential biomechanical inefficiency, though there was no difference in EMG activity in the affected and unaffected extremity.

Further longitudinal kinetic and kinematic studies involving QT ACLR subjects should be conducted as asymmetries have been associated with three times the likelihood of reinjury.[36] Additionally, kinematic and kinetic analyses of QT and BTB grafts should employ more challenging movements. For example, using motion analysis software, Paterno prospectively evaluated fifty-six athletes following ACLR during a drop vertical jump, prior to return to a pivoting sport. Patients were followed for 12 months. Thirteen athletes suffered subsequent ACL injuries. He concluded that altered neuromuscular control of the hip and knee during a dynamic landing task and postural stability deficits after ACLR are predictors of a second anterior cruciate ligament injury after an athlete is released to return to sport."[36] It is possible that these deficits may not have been seen during self-determined gait.

**Clinical Measures**

Our results supporting the use of the QT graft due to similar affected to unaffected torque ratios, and kinematic/kinetic EMG results for the BTB and QT are further supported by clinical measures. No significant differences in knee stability, graft rupture rate, or functional outcomes have been reported between QT and BTB ACLR patients.[25,34,40]

**Limitations**

Limitations to this study included variations in subjects' activity levels and adherence to rehabilitation, as well as our inability to assess subjects' willingness to provide a maximal effort during isometric testing. Bias may have also existed secondary to patient selection, as this was a convenience sample.

**Conclusion**

We hypothesized, as have others[6], that harvesting the central portion of the QT could affect torque production during leg extension through disruption of RF force production and firing patterns. The lack of significant differences in torque production and EMG quadriceps ratios between grafts in the current study caused us to reject this hypothesis, thereby supporting the use of the QT as a viable graft option for ACLR. Due to the neuromuscular and kinematic asymmetry observed, longitudinal and dynamic testing should be performed to further investigate potential alterations secondary to QT graft harvest. Future studies should evaluate quadriceps muscle firing patterns during functional dynamic activities that involve hip flexion and knee extension or test activities that are more challenging or complex in nature. Establishing consistent longitudinal quadriceps neuromuscular firing patterns and gait symmetry between QT and a healthy C group during functional activities, will provide further support for the use of QT ACLR as an appropriate primary graft option, and establish it as an appropriate surgical intervention for elite level athletes.

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**FIGURES**

Figure 1. Reflective marker placement.

Figure 2. Overview of recruitment and subject flow though the study including dropouts. (CONSORT)

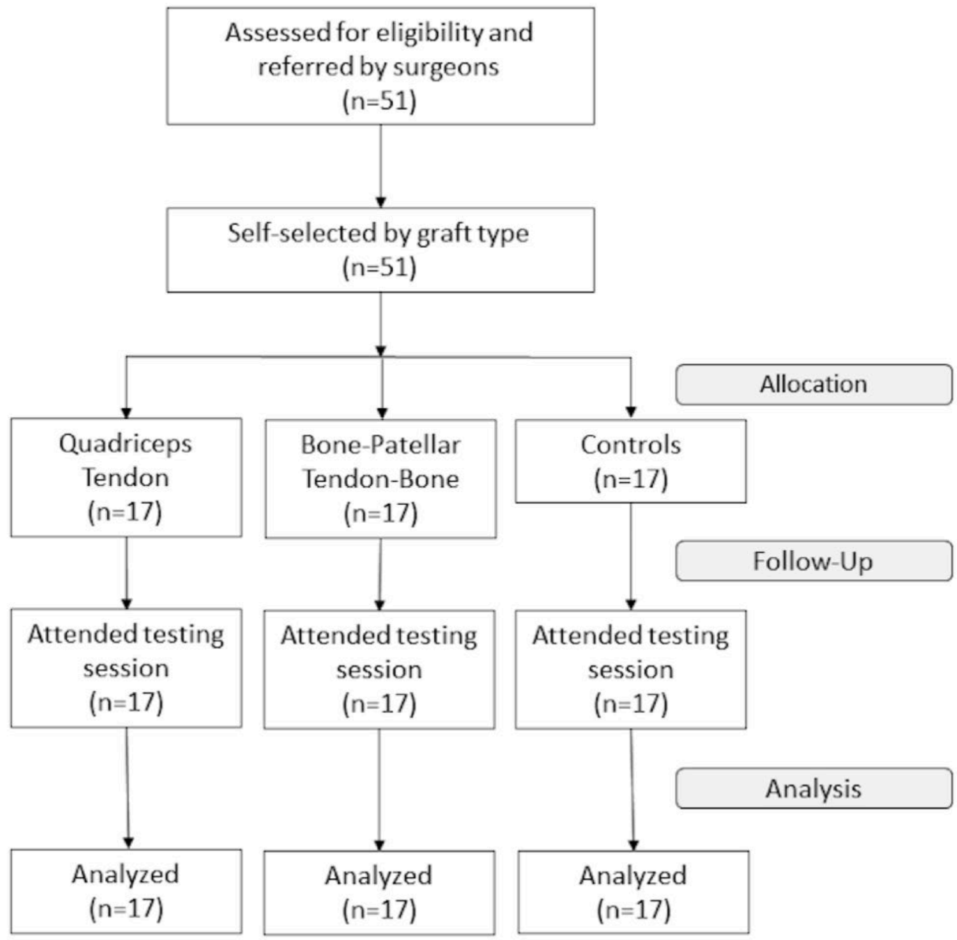
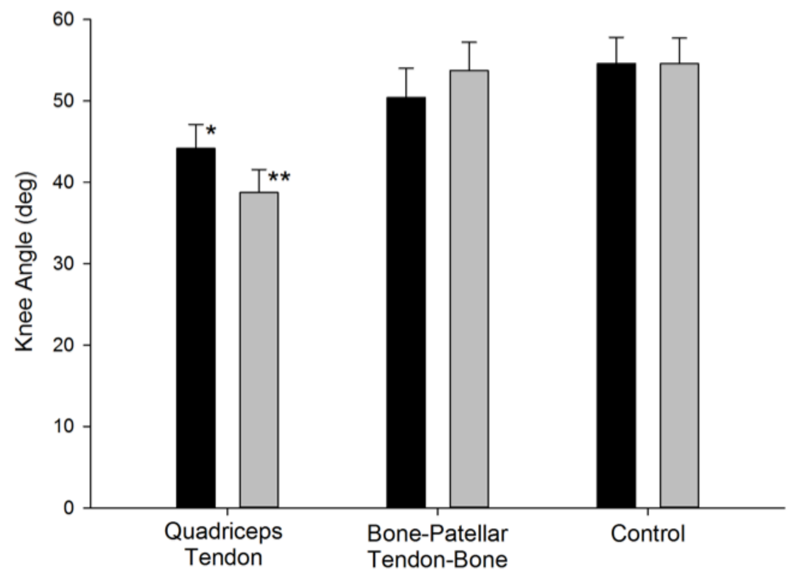
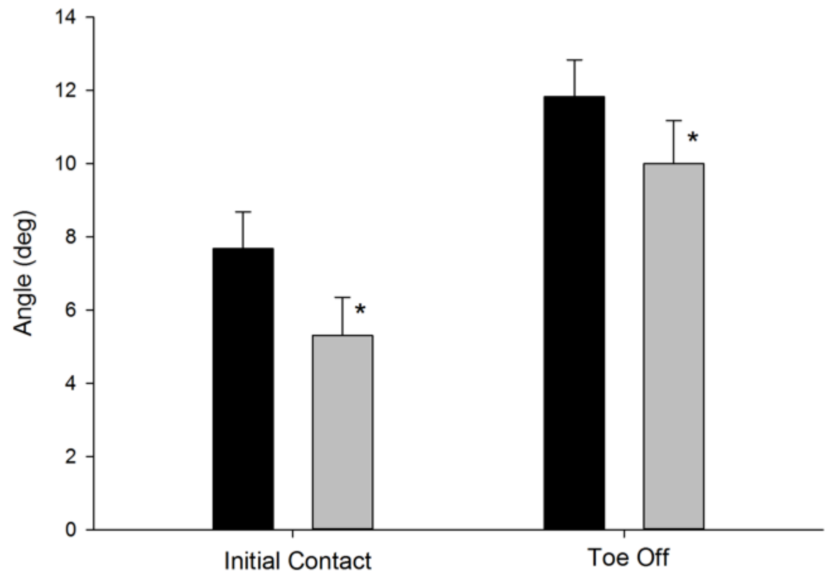


Figure 3. Maximum knee angles during the gait cycle.



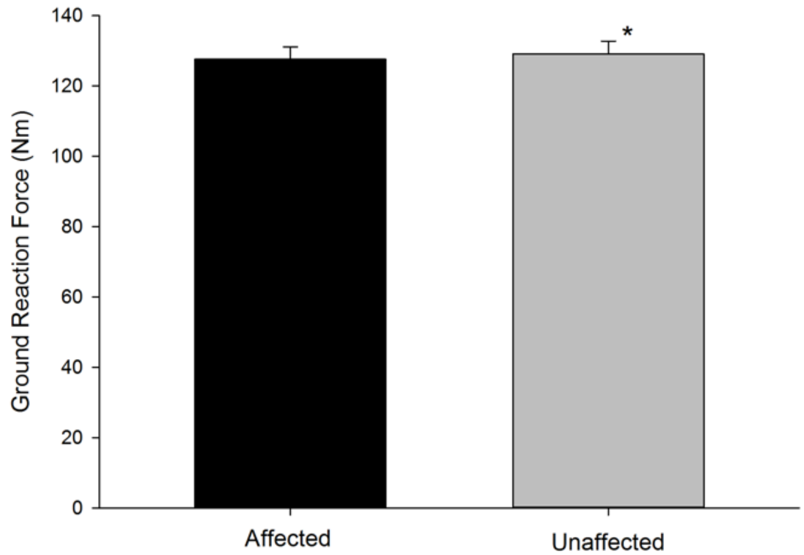

Affected ■ and unaffected knees. *Significantly lower than Controls. **Significantly lower then Controls and Bone-Patellar Tendon-Bone. Values are Means ± SE.

Figure 4. Difference in affected and unaffected knees during gait initial contact and toe off.




Affected ■ and unaffected▒knees. *Significantly lower than affected knee. Values are Means ± SE.

Figure 5. Difference in ground reaction forces for the affected and unaffected knees during gait.




Affected ■ and unaffected ▭ knees. *Significantly higher than affected knee. Values are Means ± SE.

## TABLES

Table 1. Baseline characteristics by group and overall cohort.

| | QT (n=17) | BTB (n=17) | Control (n=17) | Total Cohort | p |
|---|---|---|---|---|---|
| Age (y) | 25.8 (4.9) | 26.4 (5.0) | 25.65(5.79) | 25.8(5.15) | .732 |
| Height (m) | 1.76 (0.14) | 1.74 (0.08) | 1.74(8.89) | 1.74(10.29) | .635 |
| Weight (kg) | 84.1 (28.5) | 80.3 (14.5) | 86.13(31.17) | 83.73(25.24) | .627 |
| Sex | 13M, 4F | 13M, 4F | 10M, 7F | 36M, 15F | .427 |
| Lysholm score | 82.12 (13.24) | 89.94 (9.38) | . | 85.5(11.74) | .055 |
| IKDC | 71.71 (12.41) | 76.76 (9.03) | . | 74.15(10.97) | .184 |
| Tegner score | 6.29 (0.99) | 7.24 (1.92) | . | 6.85(1.62) | .082 |
| Time since surgery (m) | 24.9 (13.5) | 19.7 (5.0) | . | 22.71(10.18) | .165 |
| Physical Therapy (m) | 4.6 (2.5) | 5.8 (2.7) | . | 5.2(2.6) | .259 |

Table 2. Raw and adjusted means for torque differences between affected and unaffected legs.

| | Affected Leg (n = 17) | Unaffected Leg (n = 17) | Adjusted mean (SE) | | Adjusted mean difference (95% CI) | p |
|---|---|---|---|---|---|---|
| | Mean (SD) | Mean (SD) | Affected | Unaffected | | |
| Peak Torque (kg-m) | 18.05 (5.32) | 20.42 (5.42) | 18.05 (0.92) | 20.42 (0.94) | -2.37 (-4.06, -0.67) | .0001 |
| Average Torque (kg-m) | 16.67 (4.96) | 19.26 (5.12) | 16.67 (0.86) | 19.26 (0.89) | -2.59 (-3.95, -1.24) | .0001 |

SD: standard deviation; SE: standard error; CI: confidence interval

Table 3. Raw and adjusted means for differences in EMG amplitude ratios by graft and between affected and unaffected legs during isometric leg extension.

| | QT (n=17) | BTB (n=17) | QT-BTB | p |
|---|---|---|---|---|
| | Mean (SE) | Mean (SE) | Adjusted mean difference (95% CI) | |
| RF/VM ratio | 0.929 (0.140) | 0.995 (0.140) | -0.066 (-0.468, 0.336) | .740 |
| RF/VL ratio | 0.851 (0.191) | 1.095 (0.191) | -0.244 (-0.793, 0.305) | .373 |
| | Affected Leg (n = 17) | Unaffected Leg (n = 17) | QT-BTB | p |
| | Mean (SE) | Mean (SE) | Adjusted mean difference (95% CI) | |
| RF/VM ratio | 0.955 (0.135) | 0.969 (0.107) | -0.013 (-0.306, 0.280) | .928 |
| RF/VL ratio | 0.912 (0.099) | 1.304 (0.175) | -0.122 (-0.310, 0.066) | .196 |

EMG: electromyography; RF: rectus femoris; VM: vastus medialis; VL: vastus lateralis, SE: standard error; CI: confidence interval

Table 4. Raw and adjusted means for differences in EMG amplitude ratios by graft and between affected and unaffected legs during stance phase of the gait cycle.

| | QT (n=17) | BTB (n=17) | QT - BTB | p |
|---|---|---|---|---|
| | Mean (SE) | Mean (SE) | Adjusted mean difference (95% CI) | |
| RF/VM ratio | 1.00 (0.10) | .97 (0.11) | .03 (-.28, 0.34) | .84 |
| RF/VL ratio | 0.81 (0.05) | .87 (0.06) | .06 (.08, .89) | .99 |
| | Affected Leg (n = 17) | Unaffected Leg (n = 17) | Affected Leg – Unaffected Leg | p |
| | Mean (SE) | Mean (SE) | Adjusted mean difference (95% CI) | |
| RF/VM ratio | .83 (0.07) | 1.13 (0.12) | -.30 (-.55, -.05) | .07 |
| RF/VL ratio | .83(0.10) | .85 (0.08) | -.01 (-.34, .32) | .93 |

EMG: electromyography; RF: rectus femoris; VM: vastus medialis; VL: vastus lateralis, SE: standard error; CI: confidence interval

Table 5. Raw and adjusted means for differences in EMG amplitude ratios by graft and between affected and unaffected legs during swing phase of the gait cycle.

| | QT (n=17) | BTB (n=17) | QT - BTB | p |
|---|---|---|---|---|
| | Mean (SE) | Mean (SE) | Adjusted mean difference (95% CI) | |
| RF/VM ratio | 1.36 (0.09) | 1.11 (.10) | .25 (-.10, 0.59) | .25 |
| RF/VL ratio | 0.95 (0.06) | .92 (0.07) | .03 (-.19, 0.25) | 1.00 |
| | Affected Leg (n = 17) | Unaffected Leg (n = 17) | Affected Leg – Unaffected Leg | p |
| | Mean (SE) | Mean (SE) | Adjusted mean difference (95% CI) | |
| RF/VM ratio | 1.11 (.08) | 1.35 (.10) | -.24 (-.45, -.03) | .15 |
| RF/VL ratio | 0.90 (0.11) | .96 (0.10) | -.06 (-.47, .36) | .99 |

EMG: electromyography; RF: rectus femoris; VM: vastus medialis; VL: vastus lateralis, SE: standard error; CI: confidence interval