Comparison of Neuromuscular Firing Patterns of the Superficial Quadriceps in Soft Tissue Quadriceps Tendon Versus Bone–Patellar Tendon–Bone ACL Autografts

Michael Letter,*†‡ PhD, PA-C, Michael G. Baraga,† MD, Thomas M. Best,† MD, PhD, Lee D. Kaplan,‡ MD, Andrew N.L. Buskard,‡ PhD, Lauren Catena,‡ BS, Moataz Eltoukhy,†‡ PhD, Joenghoon Oh,‡ PhD, Keri Strand,‡ BS, and Joseph Signorile,†‡§ PhD

Investigation performed at the Max Orovitz Laboratory of Neuromuscular Research and Active Aging, Department of Kinesiology and Sport Sciences, University of Miami, Coral Gables, Florida, USA

Background: Soft tissue quadriceps tendon (QT) autografts are increasingly popular as a primary graft choice for anterior cruciate ligament reconstruction (ACLR), but no study has compared superficial quadriceps activity levels and leg extension strength for QT versus bone–patellar tendon–bone (BTB) autografts.

Hypothesis: Harvesting the central portion of the QT will alter rectus femoris (RF) firing patterns during maximum voluntary isometric contraction.

Study Design: Cohort study; Level of evidence, 3.

Methods: A total of 34 patients (age range, 18-40 years) who underwent ACLR using a BTB (n = 17) or QT (n = 17) autograft at a single institution participated in this study. Participants, who had no neuromuscular injury or prior surgery on either lower extremity, were at least 1 year after ACLR, and were cleared for full activity. Postoperative rehabilitation protocols were consistent across participants. Synchronized electromyography (EMG) and isometric torque data were collected from participants in the seated position with the hips flexed to 90° and the knee at 60° of flexion. Participants were asked to extend their knees as quickly as possible and perform maximum voluntary isometric contraction for 3 seconds. A practice trial and 3 test trials were completed with 30-second rest intervals. Mixed (2 graft × 2 limb) analyses of variance were used to examine differences in average and peak torque values and RF/vastus lateralis (VL) and RF/vastus medialis (VM) ratios. Lysholm and International Knee Documentation Committee (IKDC) scores were compared between groups using unpaired t tests.

Results: Significantly lower values were seen for the operative compared with the nonoperative extremity for average (P = .008; η² = 0.201) and peak torque (P < .0001; η² = 0.321), with no significant difference between graft types. Additionally, no significant differences in RF/VL or RF/VM ratios between limbs or graft types were observed.

Conclusion: At 1 year after ACLR, QT and BTB autografts showed similar isometric strength deficits, with no differences in quadriceps muscle EMG ratios seen between the 2 graft types. The results support the use of a QT autograft for ACLR, as its graft harvest does not adversely affect quadriceps firing patterns in comparison with BTB graft harvest.

Keywords: electromyography; isometric; knee; arthroscopic surgery

The use of the quadriceps tendon (QT) for anterior cruciate ligament reconstruction (ACLR) has been discussed since 1979.6 Initial autologous QT harvest techniques involved patellar bone block harvest (QTB), similar to that of a bone–patellar tendon–bone (BTB) autograft.25 Advances in technology and instrumentation have given physicians additional graft options.8 In 1999, Fulkerson15 discussed harvesting an autologous QT without incorporating the patellar bone block. Since that time, the use of the QT for ACLR has increased in prevalence. It was reported in 2010
that only 1% of surgeons were performing ACLR with a QT graft; however, in 2014, an international poll involving 20 countries found that 11% of surgeons were now performing ACLR with a QT graft. Although patients who have undergone ACLR with a QT graft have experienced good to excellent outcomes, deficits in quadriceps strength are known to persist despite ACLR, months of advanced outpatient physical therapy, and home exercise, with similar deficiencies seen in BTB and QT autografts up to 2 years after surgery. In studies comparing BTB and QT grafts in age- and sex-matched patients, Han et al found no significant difference between groups in extensor strength at 2 years after surgery, while Slone et al reported similar stability and functional outcomes, range of motion, complications, and patient satisfaction between BTB and QT grafts.

The physiological advantages of the QT versus BTB include a greater cross-sectional area with 20% more collagen, a stronger extensor mechanism, and decreased comorbidities (patellar fracture, anterior knee pain), while contraindications include prior quadriceps ruptures and chronic quadriceps tendinopathy. The QT distal attachment has been described as trilaminar, with a deep vastus intermedius layer, an intermediate adipose layer where the vastus medialis (VM) and vastus lateralis (VL) insert, and a superficial rectus femoris (RF) layer.

Although previous studies have examined extensor strength in patients after ACLR using QT and BTB grafts, no study has evaluated isometric strength and comparative levels of neuromuscular activity among the superficial quadriceps muscles of the operative versus nonoperative limbs of patients who have undergone ACLR using QT versus BTB grafts. Because of the size of the average QT patellar insertion (mean, 27 mm wide and 16 ± 2 mm deep in male and 18 ± 2 mm deep in female patients) and the superficial position of the RF aponeurosis on the QT and its direct linear pull on the patella, we theorized that QT graft harvest, which averages 6 to 7 mm in depth, 9 to 10 mm in width, and 7 to 8 mm in length, would affect quadriceps firing patterns either by increasing the RF to compensate for reduced biomechanical efficiency or by reducing activity because of compensation by the VL and VM. Therefore, we used surface EMG (sEMG) and isometric dynamometry to assess RF, VM, and VL activity and torque production, respectively, in patients with QT and BTB grafts at greater than 1 year after ACLR. By this time, most patients with BTB grafts show normal EMG activity and have returned to sport with no restrictions. We hypothesized that both groups would show decreased isometric torque values for the operative leg and that the ratio of the RF to the VM and the VL would be lower in the QT group because of graft harvest of the QT.

METHODS

Participants

This study was approved by the university’s institutional review board, and all participants were informed of the benefits and risks of the investigation before signing an institutionally approved informed consent form. A convenience sample of 34 patients who had undergone ACLR using a BTB (n = 17) or QT (n = 17) autograft at a single institution was recruited for this study. The surgical procedures were performed by 1 of 2 board-certified sports medicine orthopedic surgeons. One surgeon (M.G.B.) performed the majority of the QT ACLR procedures (15/17), while the other (L.D.K.) performed the majority of the BTB ACLR procedures (11/17). Patients were between 18 and 40 years of age and had undergone ACLR at least 1 year earlier. They had no previous neuromuscular injury or prior surgery on either lower extremity and were cleared for full activity. Potential participants were excluded from participating if they had a body mass index >35 kg/m², articular lesion(s) greater than Outerbridge grade 2 at the time of surgery, multiligament knee injuries, a postoperative Tegner activity score <4, or postoperative weightbearing or range of motion restrictions. Postoperative rehabilitation protocols were standardized in all participants; however, the duration of formal rehabilitation varied because of patient adherence and rates of progress. Anthropometric data, Lysholm knee scoring scale scores, International Knee Documentation Committee (IKDC) subjective knee evaluation form scores, and visual analog scale (VAS) satisfaction scores (range, 0-10) were collected before testing. Descriptive characteristics of the study participants are presented in Table 1.

Surgical Technique and Postoperative Treatment

QT Autograft. For the QT group, a 3-cm longitudinal incision was made to harvest the ipsilateral QT. A graft, 9 to 10 mm in width, was harvested from the central-medial portion of the QT in the fashion described by DeAngelis and Fulkerson.

BTB Autograft. A longitudinal incision was made from the inferior pole of the 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, and 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 10 mm in width.

Anatomic reconstruction was performed with both the QT and BTB. For the QT, adjustable loop suspensory fixation was used for the femur, and interference screw fixation was used on the tibia. For the BTB group, interference screw fixation was utilized on both the femur and tibia. In all reconstruction procedures, the knee was cycled before tibial fixation.

Regardless of the harvesting technique, all patients underwent standard postoperative rehabilitation protocols. Participants were encouraged to initiate physical therapy within the first week of the procedure. There were no weightbearing or range of motion restrictions for any patients. Patients were initially evaluated 7 to 10 days after the procedure for routine follow-up and were examined at regular intervals.

Patients were allowed to return to sport with no restrictions once they were deemed ligamentously stable and adequate recovery of quadriceps strength existed. All patients enrolled in this study had returned to sport with no restrictions.

Testing

A System 4 isokinetic dynamometer (Biodex) and integrated EMG collection system (MP150 System; Biopac) were used to assess isometric torque and quadriceps muscle activity, respectively.

Isometric Testing. Participants were seated on the Biodex System 4 chair, and the axle of the powerhead was aligned with the participant’s lateral condyle. Restraints were placed across the chest, waist, and knee to reduce unwanted movement. Patients’ hips and knee joints were held at 90° and 60°, respectively. Patients folded their arms across their chest and were not permitted to hold on to the equipment during the test. A total of 10 consecutive submaximal dynamic knee extensions were performed as a warm-up and to become familiar with the system and the movement before testing. There was a 3-minute break between the warm-up and testing. The warm-up was followed by 3 isometric test trials. Participants’ nonoperative limbs were tested first. Vocal encouragement during testing was standardized. Participants were asked to exert force as quickly as possible and maintain a maximal effort for 3 seconds. During all trials, participants were allowed to track their performance on the Biodex System 4 screen because visual feedback in conjunction with verbal encouragement has been shown to positively affect performance during strength testing. Participants were given a 30-second recovery between trials. Maximum voluntary isometric contraction and sEMG (RF, VM, VL) data were collected during each effort.

Electromyography. Before isometric testing, participants 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. 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) were positioned parallel to the underlying muscle fibers according to Cram’s Introduction to Surface Electromyography recommendations. Raw EMG and force data were recorded simultaneously using the Biopac MP150 System. The Biopac MP150 System has an input impedance of 1.0 MΩ and common mode rejection ratio of 110 dB at 50/60 Hz. The gain was set at 1000 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 MP150 System software. The means of the root mean square of the sEMG signal (rmsEMG) values for the RF, VM, and VL were calculated to quantify the amplitudes of each signal. Ratios were then computed between the RF and the vastus muscles (RF/VM and RF/VL) using their rmsEMG values.

Data Analysis

Peak torque (PT) and average torque (AT) were exported from the Biodex System 4 isokinetic dynamometer to the

| TABLE 1 Baseline Characteristics of Study Participants<sup>a</sup> |
|-----------------|-----------------|-----------------|-----------------|--------------|
| Overall (N = 34) | QT Group (n = 17) | BTB Group (n = 17) | P Value |
| Age, y          | 26.0 ± 4.9      | 25.8 ± 4.9      | 26.4 ± 5.0      | .732         |
| Height, m       | 1.74 ± 0.11     | 1.76 ± 0.14     | 1.74 ± 0.08     | .635         |
| Weight, kg      | 82.2 ± 22.3     | 84.1 ± 28.5     | 80.3 ± 14.5     | .627         |
| Sex, male/female, n | 24:10         | 11:6            | 13:4            | .708         |
| Lysholm score   | 86.03 ± 11.98   | 82.12 ± 13.24   | 89.94 ± 9.38    | .055         |
| IKDC score      | 74.24 ± 10.99   | 71.71 ± 12.41   | 76.76 ± 9.03    | .184         |
| Tegner score    | 6.76 ± 1.58     | 6.29 ± 0.99     | 7.24 ± 1.92     | .082         |
| VAS satisfaction score | 9.35 ± 1.25 | 9.12 ± 1.27     | 9.59 ± 1.23     | .280         |
| Time since surgery, mo | 22.4 ± 10.5 | 24.9 ± 13.5     | 19.7 ± 5.0      | .165         |
| Duration of formal PT, mo | 5.2 ± 2.6 | 4.6 ± 2.5       | 5.8 ± 2.7       | .259         |

<sup>a</sup>Values are reported as mean ± SD unless otherwise indicated. BTB, bone–patellar tendon–bone; IKDC, International Knee Documentation Committee; PT, physical therapy; QT, quadriceps tendon; VAS, visual analog scale.
Biopac MP150 System software. Raw sEMG data were windowed at 1 to 2 seconds for each trial. Mean values for rmsEMG were calculated using the Biopac MP150 System. The RF/VM and RF/VL ratios for the operative and nonoperative knees were compared to determine if the RF contribution was affected by the surgical procedure. Further, these ratios were compared for the operative knees of patients with QT and BTB grafts.

Statistical Analysis

A 2 (limb) × 2 (graft) repeated-measures analysis of variance (ANOVA), using the averages of the PT and AT values across the 3 repetitions, was performed to determine if significant differences existed in torque between the operative and nonoperative legs and the 2 graft conditions. A 3 (repetition) × 2 (limb) × 2 (graft) repeated-measures ANOVA was used to assess if differences in quadriceps EMG ratios existed between the operative and nonoperative limbs or between the operative limbs of the QT and BTB groups. When significant main effects or interactions were observed, least significant difference post hoc analyses were used to determine the source. Unpaired t tests were used to assess differences in Lysholm and IKDC scores.

To determine an optimal sample size required to provide sufficient power to establish significant differences between grafts, a power analysis was performed before the start of the study. The alpha level for significance in all tests was set a priori at 0.05. All analyses were performed using SPSS (version 17.0; IBM). Using G*Power (version 3.1.9.2), a sample size of 34 was calculated employing a statistical power of 80% with an alpha value set at 0.05, and an effect size of 0.25 was computed.14

RESULTS

Data from 34 patients, who had undergone ACLR at least 1 year before recruitment, were included in our analysis. A CONSORT (Consolidated Standards of Reporting Trials) chart showing the flow of participants through the study is presented in Figure 1.

For isometric AT, significant differences were found between the operative and nonoperative legs for the entire sample (P = .008; η² = 0.201); however, no significant main effect for graft (P = .728; η² = 0.004) or graft × leg interaction (P = .489; η² = 0.015) was detected (Table 2). This pattern was also seen for PT, where a significant main effect was seen for limb (P < .0001; η² = 0.321), while no main effect for graft (P = .618; η² = 0.008) or graft × leg interaction (P = .504; η² = 0.014) was detected (Table 2).

The analysis of the RF/VM ratio produced no significant differences among repetitions (P = .759; η² = 0.009), between operative and nonoperative legs (P = .196; η² = 0.052), or between grafts (P = .740; η² = 0.003), nor were there any significant interactions. Similarly, no significant differences were found for the RF/VL ratio among repetitions (P = .232; η² = 0.045), between operative and nonoperative legs (P = .196; η² = 0.005), or between grafts (P = .373; η² = 0.025), and once again, there was no

DISCUSSION

To our knowledge, no studies have compared EMG data of the superficial quadriceps of patients with QT and BTB grafts during maximal isometric testing. We chose to evaluate patients at greater than 1 year after surgery, as most patients show normal EMG activity8 and have returned to sport with no restrictions at that time. Our findings did not support our hypothesis that harvesting of the central portion of the QT would disrupt firing patterns of the RF. We also demonstrated that at 1 year after ACLR, QT and BTB autografts showed similar isometric strength deficits, with no differences in quadriceps muscle EMG ratios seen between the 2 grafts.

Our findings, showing an 11.6% difference in isometric PT and 18.4% difference in isometric AT between the operative and nonoperative legs of the QT group, are consistent with previous studies showing diminished quadriceps strength beyond the standard rehabilitation periods.15,16,22,23 In a group of participants 4 to 7 years after ACLR with QTB grafts, Chen and Chuang7 reported an average Lysholm score of 93.0 ± 7.9 and the recovery of 91.7% of PT in the surgical extremity when compared with the nonoperative limb. Given the substantially longer time after surgery in their group, these results were comparable
with the Lysholm score of 82.12 and PT recovery of 88.4% that we found in the QT group at a mean of 24.9 ± 13.5 months after surgery. Similarly, a study by Lee et al \(^{22}\) assessed 247 patients at an average of 44 ± 15.5 months after ACLR with QTB grafts. They reported the recovery of 79% and 81.9% in extension PT at 60 and 180 deg/s at 1 year, 81.8% and 88.4% after 2 years, and 85.1% and 91.2% after 3 years, respectively. The torque values at 1 and 2 years are comparable with the 88.4% and 81.6% values in PT and AT seen during isometric leg extension in our QT ACLR patients. Their average Lysholm score of 90 and IKDC score, reported as ranging from grade A to B, also compared well with our patients’ Lysholm score of 82.12 and IKDC score of 71.71, given that their patients’ time of assessment ranged from 25 to 87 months after surgery.

In a study comparing the results of ACLR with a QTB versus BTB graft, Han et al \(^{17}\) reported findings similar to those in our study. In 144 predominantly male patients assessed 42.1 ± 25 months and 39.7 ± 16.5 months after ACLR with BTB and QTB grafts, respectively, they found no statistical differences between IKDC or Lysholm scores between the 2 autografts (BTB: 92.8; QTB: 91.5), reflecting our findings. They also reported isokinetic torque ratios at 60 deg/s (BTB: 0.74 ± 0.20; QTB: 0.78 ± 0.13) and 180 deg/s (BTB: 0.76 ± 0.22; QTB: 0.82 ± 0.11), similar to those seen for isometric torque for the QT and BTB groups in our study at 1 year. The same pattern was reported at 2 years for isokinetic torque at 60 deg/s (BTB: 0.78 ± 0.26; QTB: 0.82 ± 0.15) and 180 deg/s (BTB: 0.80 ± 0.23; QTB: 0.89 ± 0.08). \(^{17}\)

The QT has also been compared with other tendon autografts. During a controlled randomized trial, Martin-Alguacil et al \(^{26}\) 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. They reported significantly higher hamstring-to-quadriceps ratios at 12 months for the QT versus hamstring tendon autografts. They reported significantly higher hamstring-to-quadriceps ratios at 12 months for the QT versus hamstring tendon during isokinetic testing at 60, 180, and 300 deg/s; however, there were no significant differences in Tegner, Lysholm, or Cincinnati Knee Rating System scores between groups. Although leg extension isokinetic torque was lower at all testing speeds for the QT graft, the researchers argued for its superiority because of a lower hamstring-to-quadriceps ratio, noting that this ratio would be beneficial in maintaining the hamstring’s integrity during valgus pivoting activities, which could provide greater protection for the knee.

Our results supporting the use of the QT graft because of similar operative-to-nonoperative torque ratios for the BTB and QT are further supported by clinical measures. No significant differences in knee stability, graft rupture rates, donor site morbidity, or functional outcomes have been reported between patients with QT and BTB grafts. \(^{19}\)

DeAngelis and Fulkerson \(^{11}\) 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 suprapatellar pouch. However, because of the superficial position of the RF aponeurosis on the QT 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 because of the need to compensate for reduced biomechanical efficiency or reduced activity because of compensation by the VL and VM. Our study results, showing no significant differences in EMG ratios for the superficial quadriceps between the QT and BTB groups, did not

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**TABLE 2**

| Raw and Adjusted Means for Differences in Torque for the Entire Sample\(^{2}\) |
|---------------------------------|
| **Operative Leg (n = 17)** | **Nonoperative Leg (n = 17)** | **Operative Leg (n = 34)** | **Nonoperative Leg (n = 34)** | **Adjusted Mean Difference (95% CI)** | **P Value** |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| **Peak torque, kg·m** | Mean ± SD | Mean (SE) | Mean ± SD | Mean (SE) | Mean ± SD | Mean (SE) | Mean ± SD | Mean (SE) | Mean ± SD | Mean (SE) | Mean ± SD | Mean (SE) |
| Peak torque, kg·m | 18.05 ± 5.32 | 20.42 ± 5.42 | 18.05 (0.92) | 20.42 (0.94) | −2.37 (−4.06 to −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 to −1.24) | .0001 |

\(^{2}\)SE, standard error.

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**TABLE 3**

| Raw and Adjusted Means for Differences in Electromyographic Ratios\(^{2}\) |
|---------------------------------|
| **QT Group (n = 17)** | **BTB Group (n = 17)** | **Adjusted Mean Difference (95% CI)** | **P Value** |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| **RF/VM ratio** | Mean ± SD | Mean (SE) | Mean ± SD | Mean (SE) | Mean ± SD | Mean (SE) | Mean ± SD | Mean (SE) | Mean ± SD | Mean (SE) | Mean ± SD | Mean (SE) |
| RF/VM ratio | 0.929 (0.140) | 0.995 (0.140) | −0.066 (−0.468 to 0.336) | .740 |
| RF/VL ratio | 0.955 (0.135) | 1.095 (0.191) | −0.244 (−0.793 to 0.305) | .373 |
| **Adjusted Mean Difference (95% CI)** | **P Value** |
| **Affected Leg (n = 34)** | **Unaffected Leg (n = 34)** | **Adjusted Mean Difference (95% CI)** | **P Value** |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| **RF/VM ratio** | Mean ± SD | Mean (SE) | Mean ± SD | Mean (SE) | Mean ± SD | Mean (SE) | Mean ± SD | Mean (SE) | Mean ± SD | Mean (SE) | Mean ± SD | Mean (SE) |
| RF/VM ratio | 0.955 (0.135) | 0.969 (0.107) | −0.013 (−0.306 to 0.280) | .928 |
| RF/VL ratio | 0.912 (0.099) | 1.304 (0.175) | −0.122 (−0.310 to 0.066) | .196 |

\(^{2}\)Values are reported as mean (standard error) unless otherwise indicated. BTB, bone–patellar tendon–bone; QT, quadriceps tendon; RF, rectus femoris; VL, vastus lateralis; VM, vastus medialis.
support this hypothesis. Possibly, the graft harvest size was not sufficient to affect the mechanical pull of the RF or require compensatory firing of the vasti muscles.

Results of the present study support previous studies that investigated potential neuromuscular alterations after ACLR. Knoll et al.\(^\text{21}\) found no significant EMG differences during treadmill walking at 3.0 km/h in patients who underwent ACLR compared with healthy controls 8 months after BTB surgery. Bulgheroni et al.\(^\text{5}\) examined EMG activities of the RF, VL, biceps femoris, and semitendinosus in 15 patients 17 ± 5 months after BTB surgery and reported no significant difference in EMG patterns of the VL or RF during overground gait between patients who underwent ACLR and controls. Additionally, Cicotti et al.\(^\text{8}\) found EMG activities of the VL, RF, and VM 8 to 12 months after ACLR to be very similar to those of healthy controls.

One limitation that may have affected our results was our sample size of 34 participants. Although this was the computed sample size provided by our power analysis, studies with a larger number of patients are warranted. A second limitation is that the number of ACLR procedures with QT and BTB grafts was not consistent between the 2 surgeons; therefore, results may have been affected by differences in the surgical technique. Additional limitations included variations in participants' activity levels and adherence to rehabilitation as well as our inability to assess participants' willingness to provide a maximal effort during isometric testing. Bias may have also existed secondary to patient selection, which resulted in unequal recruitment between surgeons who may have differed in the surgical technique, as this was a convenience sample. Additionally, the larger number of men compared with women in our sample is not reflective of the higher risk reported in women compared with men.

CONCLUSION

We hypothesized, as have others,\(^\text{6}\) 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 between operative and nonoperative legs and EMG quadriceps ratios between QT and BTB grafts in the current study caused us to reject this hypothesis. Longitudinal and dynamic testing should be performed to further investigate potential neuromuscular 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. Establishing consistent quadriceps firing patterns between QT and BTB autografts during functional activities will provide further support for the use of the QT as an appropriate primary graft option and establish ACLR as an appropriate surgical intervention for elite-level athletes.

REFERENCES

1. Adams DJ, Mazzocca AD, Fulkerson JP. Residual strength of the quadriceps versus patellar tendon after harvesting a central free tendon graft. *Arthroscopy*. 2006;22(1):76-79.
2. Basmajian JV, De Luca CJ. Description and analysis of the EMG signal. In: *Muscles Alive: Their Functions Revealed by Electromyography*. Baltimore, Maryland: Williams & Wilkins; 1985:97-99.
3. Baweja HS, Patel BK, Martinzewicz JD, Vu J, Christou EA. Removal of visual feedback alters muscle activity and reduces force variability during constant isometric contractions. *Exp Brain Res*. 2009;197(1):35-47.
4. Bulgheroni P, Bulgheroni MV, Andrini L, Guelfini P, Giughello A. Gait patterns after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 1997;5(1):14-21.
5. Campenella B, Mattacola CG, Kimura IF. Effect of visual feedback and verbal encouragement on concentric quadriceps and hamstrings peak torque of males and females. *Isokin Exerc Sci*. 2000;8(1):61-62.
6. Cavanagh PR, Komi PV. Electromechanical delay in human skeletal muscle under concentric and eccentric contractions. *Exp J Appl Physiol Occup Physiol*. 1979;42(3):159-163.
7. Chen CH, Chuang TY. Arthroscopic anterior cruciate ligament reconstruction with quadriceps tendon autograft: clinical outcome in 4-7 years. *Knee Surg Sports Traumatol Arthrosc*. 2006;14(11):1077-1085.
8. Cicotti MG, Kerlan RK, Perry J, Fink M. An electromyographic analysis of the knee during functional activities. *J Orthop*. 1994;22(5):651-658.
9. Crall TS, Gilmer BB. Anatomic all-inside anterior cruciate ligament reconstruction using quadriceps tendon autograft. *Arthroscopy*. 2015;4(6):841-845.
10. Criswell E. Cram’s Introduction to Surface Electromyography. Boston: Jones and Bartlett Publishers; 2011.
11. DeAngelis JP, Fulkerson JP. Quadriceps tendon: a reliable alternative for reconstruction of the anterior cruciate ligament. *Clin Sports Med*. 2007;26(4):587-596.
12. De Jong SN, van Caspel DR, van Haeff MF, Saris DB. Functional assessment and muscle strength before and after reconstruction of chronic anterior cruciate ligament lesions. *Arthroscopy*. 2007;23(1):21-28.
13. Drechsler WI, Cramp MC, Scott OM. Changes in muscle strength and EMG median frequency after anterior cruciate ligament reconstruction. *Eur J Appl Physiol*. 2006;98(6):613-623.
14. Faul F, Erdfelder E, Buchner A, Lang AG. Statistical power analysis using G*Power 3.1: tests for correlation and regression analysis. *Behav Res Methods*. 2009;41(4):1149-1160.
15. Fulkerson JP. Central quadriceps free tendon for anterior cruciate ligament reconstruction. *Oper Tech Sports Med*. 1999;7(4):195-200.
16. Gillquist J, Messner K. Anterior cruciate ligament reconstruction and the long term incidence of gonarthrosis. *Sports Med*. 1999;27(3):143-156.
17. Han HS, Seong SC, Lee S, Lee MC. Anterior cruciate ligament reconstruction: quadriceps versus patellar autograft. *Clin Orthop Relat Res*. 2008;466(1):198-204.
18. Harris NL, Smith DA, Lamoreaux L, Purnell M. Central quadriceps tendon for anterior cruciate ligament reconstruction, part I: morphometric and biomechanical evaluation. *Am J Sports Med*. 1997;25(1):23-28.
19. Hurley ET, Calvo-Gurry M, Withers D, Farrington SK, Moran R, Moran CJ. Quadriceps tendon autograft in anterior cruciate ligament reconstruction: a systematic review. *Arthroscopy*. 2018;34(5):1690-1698.
20. Kim SJ, Kumar P, Oh KS. Anterior cruciate ligament reconstruction: autogenous quadriceps tendon-bone compared with bone-patellar tendon-bone grafts at 2-year follow-up. *Arthroscopy*. 2009;25(2):137-144.
21. Knoll Z, Kiss RM, Kocsis L. Gait adaptation in ACL deficient patients before and after anterior cruciate ligament reconstruction surgery. *J Electromyogr Kinesiol*. 2004;14(3):287-294.
22. Lee S, Seong SC, Jo CH, Han HS, An JH, Lee MC. Anterior cruciate ligament reconstruction with use of autologous quadriceps tendon graft. *J Bone Joint Surg Am*. 2007;89(Suppl 3):116-126.
23. Lo Presti C, Kirkendall DT, Street GM, Dudley AW. Quadriceps insufficiency following repair of the anterior cruciate ligament. *J Orthop Sports Phys Ther*. 1988;9(7):245-249.
24. Lorentzon R, Elmquist LG, Sjöström M, Fagerlund M, Fugl-Meyer AR. Thigh musculature in relation to chronic anterior cruciate ligament tear: muscle size, morphology, and mechanical output before reconstruction. Am J Sports Med. 1989;17(3):423-429.
25. Marshall JL, Warren RF, Wickiewicz TL, Reider B. The anterior cruciate ligament: a technique of repair and reconstruction. Clin Orthop Relat Res. 1979;143:97-106.
26. Martin-Alguacil JL, Arroyo-Morales M, Martin-Gomez JL, et al. Strength recovery after anterior cruciate ligament reconstruction with quadriceps tendon versus hamstring. Knee. 2018;25(4):704-714.
27. Middleton KK, Hamilton T, Irrgang JJ, Karlsson J, Harner CD, Fu FH. Anatomic anterior cruciate ligament (ACL) reconstruction: a global perspective. Part 1. Knee Surg Sports Traumatol Arthrosc. 2014;22(7):1467-1482.
28. Pfeifer K, Banzer W. Motor performance in different dynamic tests in knee rehabilitation. Scand J Med Sci Sports. 1999;9(1):19-27.
29. Slone HS, Romine SE, Premkumar A, Xerogeanes JW. Quadriceps tendon autograft for anterior cruciate ligament reconstruction: a comprehensive review of current literature and systematic review of clinical results. Arthroscopy. 2015;31(3):541-554.
30. Suter E, Herzog W, Bray R. Quadriceps activation during knee extension exercises in patients with ACL pathologies. J Appl Biomech. 2001;17(2):87-102.
31. Van Eck CF, Illingworth KD, Fu FH. Quadriceps tendon: the forgotten graft. Arthroscopy. 2010;26(4):441-442.
32. Yasuda K, Ohkoshi Y, Tanabe Y, Kaneda K. Muscle weakness after anterior cruciate ligament reconstruction using patellar and quadriceps tendons. Bull Hosp Jt Dis Orthop Inst. 1991;51(2):175-185.