

Association Between Neuromuscular Variables and Graft Harvest in Soft Tissue Quadriceps Tendon Versus Bone–Patellar Tendon–Bone Anterior Cruciate Ligament Autografts

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Background: Quadriceps tendon (QT) autografts are increasingly popular for anterior cruciate ligament reconstruction (ACLR). However, no study has compared QT autografts with bone–patellar tendon–bone (BTB) autografts regarding the electromechanical delay (EMD), the peak torque (PT), and the rate of force development (RFD) in the superficial quadriceps muscles (rectus femoris [RF], vastus medialis [VM], and vastus lateralis [VL]).

Hypotheses: We hypothesized (1) there would be a significantly lower PT, lower RFD, and longer quadriceps EMD of the operative limb for the QT versus the BTB autograft; (2) the PT, the RFD, and the quadriceps EMD of the operative limb would be significantly depressed compared with those of the nonoperative limb, regardless of the surgical technique; and (3) there would be greater increases in the RF EMD than in the VM or the VL EMD.

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

Methods: A total of 34 patients (age, 18–40 years), who had undergone ACLR (QT, $n = 17$; BTB, $n = 17$) at least 1 year before testing and performed 3 perceived maximal effort isometric tests, which were time synchronized with surface electromyography (EMG) on their operative and nonoperative limbs, were included in this study. EMD, PT, and RFD data were analyzed using a 2 (limb) \times 2 (graft) \times 3 (repetition) mixed repeated-measures analysis of variance.

Results: The EMD, the PT, and the RFD were not significantly affected by graft choice. For the VL, a significant repetition \times graft \times limb interaction was detected for the VL EMD ($P = .027$; $\eta^2_p = 0.075$), with repetition 3 having longer EMD than repetition 2 (mean difference [MD], 16 milliseconds; $P = .039$). For the RF EMD, there was a significant repetition \times limb interaction ($P = .027$; $\eta^2_p = 0.074$), with repetition 3 being significantly longer on the operative versus the nonoperative limb (MD, 24 milliseconds; $P = .004$). Further, the operative limb EMD was significantly longer for repetition 3 versus repetition 2 (MD, 17 milliseconds; $P = .042$). For the PT, there was a significant effect for repetition ($P = .003$; $\eta^2_p = 0.114$), with repetition 1 being significantly higher than both repetitions 2 (MD, 8.52 N·m; $P = .001$) and 3 (MD, 7.79 N·m; $P = .031$). For the RFD, significant limb ($P = .034$; $\eta^2_p = 0.092$) and repetition ($P = .010$; $\eta^2_p = 0.093$) effects were seen, with the nonoperative limb being significantly faster than the operative limb (MD, 23.7 N·m/s; $P = .034$) and repetition 1 being significantly slower than repetitions 2 (MD, -20.46 N·m/s; $P = .039$) or 3 (MD, -29.85 N·m/s; $P = .002$).

Conclusion: The EMD, the PT, and the RFD were not significantly affected by graft type when comparing QT and BTB autografts for ACLR; however, all neuromuscular variables were affected regardless of the QT or the BTB harvest.

Keywords: arthroscopy; electromyography; isometric; knee

The Orthopaedic Journal of Sports Medicine, 9(10), 23259671211041591
DOI: 10.1177/23259671211041591
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The use of quadriceps tendon (QT) autografts for anterior cruciate ligament (ACL) reconstruction (ACLR), which may include but does not necessitate a patellar bone block,¹⁵ has increased exponentially³⁴ since the original description of this harvesting technique. The QT approach has been

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presented as a viable alternative to the more traditional bone–patellar tendon–bone (BTB) graft, given the physiological and biomechanical advantages associated with its use.² The BTB graft has been reported to have high strength, stiffness, and ease of harvesting.¹² In contrast, the QT autograft has been described as having a greater cross-sectional area, a higher collagen content, and a decreased likelihood of anterior knee pain.^{10,21} However, its use is contraindicated in those with prior quadriceps rupture or tendinopathy.⁸

While electromyography (EMG) is a commonly used tool for examining the electrical activity of the superficial quadriceps muscles during the rehabilitation period after ACLR, most analyses have been performed after BTB ACLR.^{7,28,35,36} Only 2 studies, to our knowledge, have compared activity levels of these muscles after BTB and QT ACLR, and both concluded that they are equally viable graft options.^{23,32}

The electromechanical delay (EMD), a special application of EMG, is defined as the time elapsed between the onset of muscle electrical activation and the onset of force production.^{3,5} The EMD may be considered an important measure after ACLR, as major factors affecting this delay include the compliance of the musculotendinous components, the size of the muscle, and the maximal isometric voluntary contraction force (MVC), each of which may be adversely affected by the surgery.¹⁶ Studies have shown that EMDs of selected muscles of the hamstrings group are prolonged after ACLR using semitendinosus and gracilis tendons^{14,25,39}; however, results from a single study examining EMD of the quadriceps after BTB ACLR showed no significant effect for the rectus femoris (RF) or vastus medialis (VM) muscles.¹⁶

Protracted EMD has been associated with reductions in explosive performance^{20,41} and increased injury potential.²⁰ Further, prolonged quadriceps EMD has been reported after ACLR¹⁷ and in patients with patellofemoral pain syndrome.⁶ The EMD is also a viable marker of both the success and the specificity of training interventions.^{17,19} Clinicians should consider the EMD as an additional neuromuscular variable for determining the initiation of the dynamic components of a rehabilitation program and subsequent return to sports. As a measure of the time required to generate force, the EMD is a critical factor affecting power production, especially in explosive sports⁴²; therefore, prolonged EMD would reduce performance, and these reductions would be further exacerbated if the delay were increased through fatigue.^{16,31} Alterations in the compliancy of the series elastic components after ACLR scar tissue or other immediate structural changes

may also cause protracted EMD, thereby reducing the levels of stored elastic energy and slowing reaction time. This would reduce the individual's capacity to react to external stimuli, increase movement costs, and modify the kinetic chain of motion, thereby increasing the likelihood of reinjury.¹⁶ Finally, as prolonged EMD may affect the stability of the knee by delaying the dynamic restraint to injury, its inclusion as a measure of the athlete's capacity to return to sports should be considered.¹³

Although the use of QT grafts for ACLR has become more common in recent years, the literature comparing the EMD when utilizing different grafts for reconstruction is scarce. Therefore, the objective of this research was (1) to compare the EMD of patients' operative limb 1 year after ACLR using QT or BTB autografts versus controls and (2) to compare patients' operative limb to their nonoperative limb. Additionally, the peak torque (PT) and the rate of force development (RFD) were compared between autografts and the operative versus the nonoperative limb, as each measure is used to evaluate patients' knee stability,⁴³ readiness to return to play,¹ and likelihood of noncontact ACL reinjury.¹

We hypothesized that there would be a significantly lower PT, lower RFD, and longer EMD of the superficial quadriceps muscles (RF, VM, and vastus lateralis [VL]) of the operative limb for the QT when compared with the BTB autograft in patients at least 1 year after ACLR. Additionally, we hypothesized that the PT, the RFD, and the quadriceps EMD of the operative limb would be significantly depressed compared with those of the nonoperative limb, regardless of the surgical technique utilized. Finally, we hypothesized that because of the superficial position of the RF aponeurosis on the QT, there would be greater increases in the EMD for the RF than for the VM or the VL.¹⁰

METHODS

Study Design

This cohort study involved patients who had undergone QT and BTB ACLR with a minimum 1-year follow-up. The study was approved by an institutional review board, and all participants provided informed consent.

Participants

This cohort employed a convenience sample of 34 patients who had ACLR surgery at least 1 year before testing and were recruited between May 2018 and June 2018 for the

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Final revision submitted April 23, 2021; accepted June 9, 2021.

One or more of the authors has declared the following potential conflict of interest or source of funding: M.G.B. has received education payments and consulting fees from Arthrex and hospitality payments from Smith & Nephew. T.M.B. has received hospitality payments from GE Healthcare. L.D.K. has received education payments and speaking fees from Arthrex and royalties from Smith & Nephew. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval for this study was obtained from the University of Miami (ID No.: 20180152).

current study. Inherent risks and benefits of both QT and BTB autografts were discussed with the patient before surgery, and graft selection was determined by the patient. All data of the patients included in the current analysis were collected during June and July of 2018 in our sport medicine laboratory.

Patients underwent ACLR using either the BTB ($n = 17$) or the QT ($n = 17$) autograft. Two fellowship-trained sports medicine surgeons (M.G.B., L.D.K.) experienced in harvesting both BTB and QT autografts completed the procedures. One surgeon (M.G.B.) performed the majority of the QT ACLRs (15/17) and the other surgeon (L.D.K.) performed the majority of the BTB ACLRs (11/17). Patients' ages ranged from 18 to 40 years, and all had undergone ACLR at least 1 year before testing. Patients were cleared for activity and had no previous neuromuscular pathology or prior surgery on either lower extremity. Potential patients were not included in the study if they had a body mass index >35 , articular lesions greater than Outerbridge grade 2 at the time of surgery, multiligament knee injury, or a Tegner activity score <4 (range, 0 = sick leave to 10 = top level competitive sport).⁴⁰ All patients underwent the same postoperative rehabilitation protocols at the same center; however, the length of rehabilitation varied by patient adherence and progress. Anthropometric data, the Lysholm knee scoring scale, and International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form data were collected during 1 session immediately before testing.

Surgical Technique and Postoperative Treatment

All patients underwent the procedure with general anesthesia and the use of a tourniquet. BTB grafts were harvested from the central-third of the patellar tendon, 1 cm in width with bone blocks between 20 and 25 mm in length. Grafts were sized 10 mm in diameter. For the QT group, a 3-cm longitudinal incision was made to harvest the ipsilateral QT. QT grafts measuring 9 to 10 mm in width were harvested from the central-medial portion of the tendon in the fashion described by DeAngelis and Fulkerson.¹⁰ Anatomic reconstruction of the QT was performed using adjustable loop suspensory fixation for the femur and interference screw fixation on the tibia. During the BTB harvest, a longitudinal incision was made from the inferior pole of the patella to the medial aspect of the tibial tubercle. Initially, a 10-mm central portion of the patellar tendon was delineated, and then cuts were performed using 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. For the BTB group, interference screw fixation was utilized on both the femur and the tibia. In all reconstruction procedures, the knee was cycled before tibial fixation.

Range of motion braces were given to all patients to wear for 4 weeks postoperatively. Participants were encouraged to initiate physical therapy within the first week of the procedure. All patients adhered to the same rehabilitation protocol. Time-specific parameters for the phases of rehabilitation were the same for all patients and included jogging at 3 months and lateral movement/cutting at 5 months. No meniscal repairs were required, and 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 sports with no restrictions once the ligament was deemed stable and adequate recovery of quadriceps strength existed. The threshold for quadriceps strength recovery was a deficit $<10\%$ in the operative limb compared with the contralateral limb on isometric/isokinetic strength testing. As noted in our previous manuscript,³² at the time of testing, significantly lower values were seen for the operative compared with the nonoperative extremity for average torque (operative: 16.67 ± 0.86 kg·m; nonoperative: 19.26 ± 0.89 kg·m [$P < .008$; $\eta^2 = 0.201$]) and the PT (operative: 18.05 ± 0.92 kg·m; nonoperative: 20.42 ± 0.92 kg·m; [$P < .0001$; $\eta^2 = 0.321$]), indicating deficits of 13.5% and 11.6%, respectively. No significant differences were found between graft types or between limbs or graft types in RF:VL or RF:VM ratios.

Testing

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

Isometric Testing. Participants were seated on the Biodex chair, and the axle of the powerhead was aligned with their lateral condyle. Restraints were placed across the chest at the waist and across the knee to reduce unwanted movement, and patients were instructed to gently cross their arms over their chests during testing. Patients were familiarized with the system before testing. Each patient performed 10 consecutive submaximal isoinertial movements as a warm-up. After a 3-minute recovery, 3 isometric test trials were performed, with patients' hip and knee joints held at 90° and 60° , respectively. Patients' nonoperative limbs were tested first. Vocal encouragement was standardized during the testing. Patients were asked to exert force as quickly as possible and maintain a maximal effort for 3 seconds. During all trials, patients were allowed to track their performance on the Biodex screen, as visual feedback in conjunction with verbal encouragement has been shown to positively affect performance during strength testing.^{2,4} Participants were given a 30-second recovery between trials. Isometric MVC and surface EMG (sEMG) (RF, VM, and VL) data were collected during each effort.

Electromyography. Before the isometric testing, patients were prepared for sEMG data collection. A bipolar surface configuration was used to maximize the reception area while controlling for potential crosstalk among the muscles of the quadriceps group. The skin overlying each muscle was shaved, abraded, and cleansed using rubbing alcohol to remove dead surface tissues and oils, thereby reducing impedance for the skin-electrode interface. Disposable Ag/AgCl dual electrodes (Noraxon Inc) were positioned parallel to the underlying muscle fibers according to *Cram's Introduction to Surface Electromyography* recommendations.⁹ Raw EMG and force data were recorded simultaneously

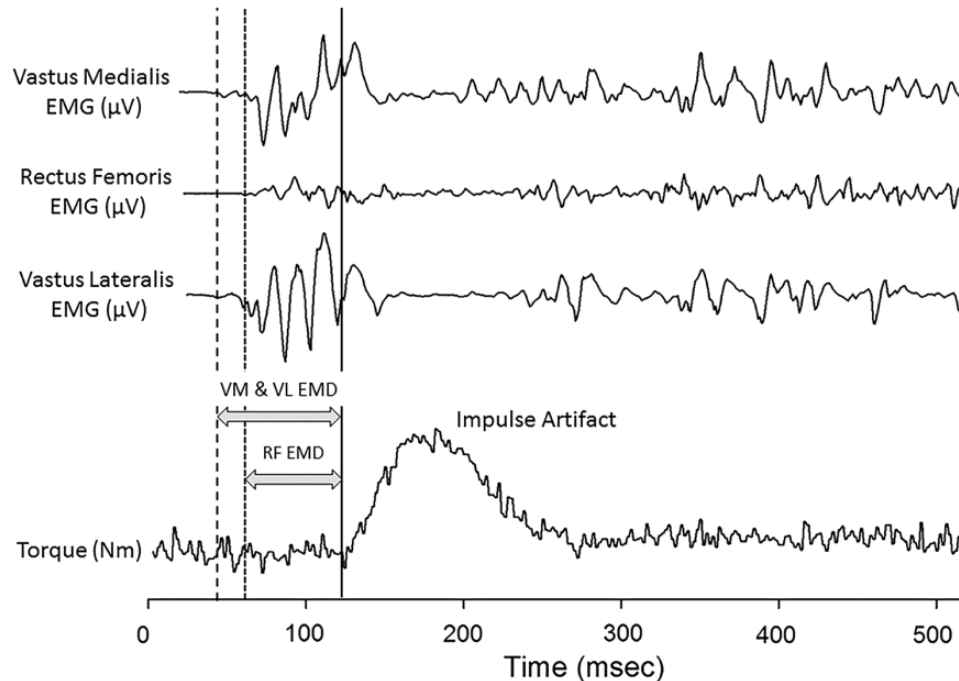


Figure 1. Graphic representations of EMD (see vertical lines) for the VM, the RF, and the VL. EMD, electromechanical delay; EMG, electromyography; RF, rectus femoris; VL, vastus lateralis; VM, vastus medialis.

using the Biopac MP150 system. The Biopac MP150 system has an input impedance of 1.0 M Ω and common mode rejection ratio of 110 dB (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 analog-to-digital converter, and stored on a laptop laboratory computer. Recorded EMG signals from each muscle were analyzed using the Biopac MP150 Acqknowledge system software.

Data Analysis

Electromechanical Delay. The EMD was assessed during the isometric testing according to the methods described by Howatson et al²² for use with the Biodex dynamometer where cushion compression may be an issue, in which thresholds for the EMG and the torque were 2 standard deviations (SDs) above mean baseline values.² Briefly, using the Biopac Acqknowledge software, we computed the EMD as the time between the onset of EMG activity for each muscle and the initiation of torque production during the effort. A 2-SD threshold value above the mean resting activity was used to determine the onset of EMG and torque production. The reliability of this method has been previously established (coefficient of variation, <6.5%).²² A visual representation of the test is presented in Figure 1.

Peak Torque. The PT was also calculated utilizing the analysis functions in the Biopac Acqknowledge software. The torque curve was highlighted for each repetition, and a maximum value was generated within the selected area.

The software generated these values in volts, which were converted to newton meters using the conversion factor for the Biodex 4 presented by Kuenze et al.²⁹

Rate of Force Development. The RFD was determined using the slope of the torque curve. This value was auto-generated by the Biopac Acqknowledge software. The beginning of the torque curve was determined by selecting the point at which the curve increased 2 SDs above the mean. The regression line was then generated from that point to the point of PT. The software generated the slope in volts per second, which was then manually converted to newton meters per second using the specified conversion factor.²⁹

Statistical Analysis

For each muscle, a 2 (limb) \times 2 (graft) \times 3 (repetition) mixed repeated-measures analysis of variance was performed to determine whether significant differences in the EMD, the PT, or the RFD existed between the affected and unaffected legs, between the 2 graft conditions, or among test repetitions. When significant main effects or interactions were observed, least squares difference post hoc analyses were used to determine the source. Paired *t* tests were used to assess differences in the Lysholm and IKDC scores. Finally, comparisons were made between Tegner scores, time since surgery, and duration of physical therapy and between each measure to determine whether Tegner scores affected our results. The alpha level for significance in all tests was set a priori at .05. All analyses were performed using SPSS

(Version 17.0; IBM Corp). Using G*Power (Version 3.1.9.2; Universitat Dusseldorf, Germany), a total sample size of 26 was calculated employing a statistical power of 85%, an alpha value of .05, and an *f* effect size of 0.25.

RESULTS

A CONSORT (Consolidated Standards of Reporting Trials) chart showing the movement of the 34 patients through the study is presented in Figure 2, and patient characteristics are presented in Table 1.

Electromechanical Delay

No significant main effects or interactions were found for the VM EMD. For the VL, a significant repetition × graft ×

limb interaction was detected ($P = .027$; $\eta_p = 0.075$). Neither the graft × limb nor the graft × repetition pairwise comparisons revealed any significant differences. However, an examination of the limb × repetition interaction revealed that, on the operative limb, repetition 3 showed a significantly longer EMD than did repetition 2 (mean difference [MD], 16 milliseconds; [95% confidence interval (CI), 1-30 milliseconds]; $P = .039$) for the VL. For the RF EMD, there was a significant repetition × limb interaction ($P = .027$; $\eta_p = 0.074$). Pairwise comparisons, analyzing differences between limbs for each repetition, showed that the EMD for repetition 3 was significantly longer on the operative limb than the nonoperative limb (MD, 24 milliseconds [95% CI, 8-40 milliseconds]; $P = .004$). When comparing repetitions on each limb, on the operative limb a significantly longer EMD was seen for repetition 3 compared with repetition 2 (MD, 17 milliseconds [95% CI, 1-34 milliseconds]; $P = .042$). A visual illustration of the results for the EMD are presented in Figure 3.

Peak Torque

In the analysis for the PT, no significant main effects or interactions were found for the limb or the graft; however, there was a significant main effect for repetition ($P = .003$; $\eta_p = 0.114$). The PT for repetition 1 was significantly higher than for repetition 2 (MD, 8.52 N·m [95% CI, 3.84 to 13.19 N·m]; $P = .001$) and repetition 3 (MD, 7.79 N·m [95% CI, -0.39 to 14.64 N·m]; $P = .062$).

Rate of Force Development

For the RFD, significant main effects were detected for the limb ($P = .034$; $\eta_p = 0.092$) and repetition ($P = .010$; $\eta_p = 0.093$). Pairwise analyses results showed that the RFD was significantly faster on the nonoperative limb compared with the operative limb (MD, 23.7 N·m/s [95% CI, 1.89 to 45.51 N·m/s]; $P = .034$), while the RFD for repetition 1 was significantly slower than for repetition 2 (MD, -20.46 N·m/s [95% CI, -39.89 to -1.03 N·m/s]; $P = .039$) or repetition 3 (MD, -29.85 N·m/s [95% CI, -48.52 to -11.16 N·m/s]; $P = .002$). No other main effects or interactions

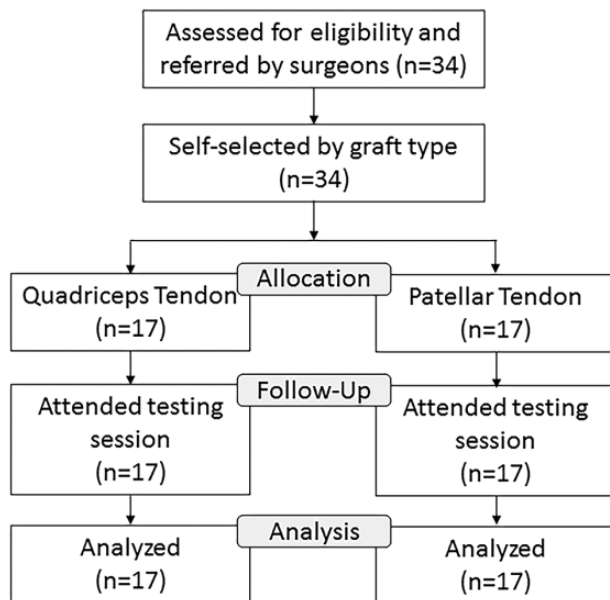


Figure 2. CONSORT (Consolidated Standards of Reporting Trials) chart of patients through the study.

TABLE 1
Descriptive Characteristics of Study Participants^a

	Entire Sample (N = 34)	Quadriceps Tendon (n = 17)	Patellar Tendon (n = 17)	<i>P</i>
Age, y	26 ± 4.9	25.8 ± 4.9	26.4 ± 5	.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 (range, 0-100)	86.03 ± 11.98	82.12 ± 13.24	89.94 ± 9.38	.055
IKDC (range, 0-100)	74.24 ± 10.99	71.71 ± 12.41	76.76 ± 9.03	.184
Tegner score (range, 0-10)	6.76 ± 1.58	6.29 ± 0.99	7.24 ± 1.92	.082
Satisfaction score (range, 0-10)	9.4 ± 1.3	9.1 ± 1.3	9.6 ± 1.2	.280
Time since surgery, mo	22.4 ± 10.5	24.9 ± 13.5	19.7 ± 5.0	.165
Physical therapy, mo	5.2 ± 2.6	4.6 ± 2.5	5.8 ± 2.7	.259

^aValues are reported as mean ± SD unless otherwise indicated. IKDC, International Knee Documentation Committee.

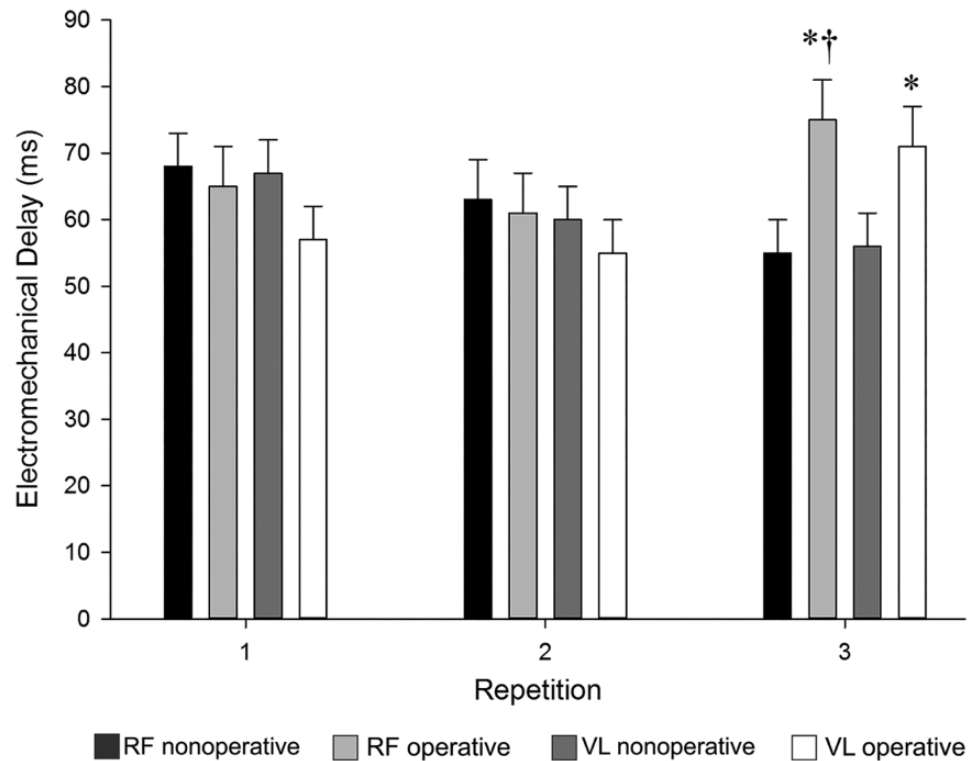


Figure 3. Differences in the electromechanical delay among repetitions and between limbs for the rectus femoris (RF) and the vastus lateralis (VL). *Significantly longer EMD than repetition 2 ($P < .05$). †Significantly different from the nonoperative limb for repetition 3 ($P < .05$).

TABLE 2
Comparison of PT and RFD by Repetition and Limb^a

Variable	Operative Limb (Mean ± SD)	Nonoperative Limb (Mean ± SD)	MD _{Rep} (95% CI)	P_{Rep}	MD _{Limb} (95% CI)	P_{Limb}
PT, N·m						
Repetition 1	185.67 ± 48.60	206.91 ± 56.26	—	—	18.48 (−8.4 to 45.90)	.182
Repetition 2	178.11 ± 43.37	197.90 ± 51.95	8.52 (3.84 to 13.19)	.001	—	—
Repetition 3	181.79 ± 42.45	196.01 ± 48.30	7.79 (−0.39 to 14.64)	.062	—	—
RFD, N·m/s						
Repetition 1	74.31 ± 31.43	97.55 ± 48.66	—	—	23.70 (1.89 to 45.51)	.034
Repetition 2	100.29 ± 67.69	112.71 ± 52.54	−20.46 (−39.89 to −1.03)	.039	—	—
Repetition 3	96.99 ± 44.09	135.33 ± 72.51	−29.85 (−48.52 to −11.16)	.002	—	—

^aBolded P values indicate statistical significance ($P < .05$). Dashes signify areas not applicable. Limb, operative versus nonoperative limbs; MD, mean difference; PT, peak torque; Rep, repetition; RFD, rate of force development.

reached significance. Comparisons among repetitions for the PT and the RFT and between limbs for these 2 variables are presented in Table 2.

DISCUSSION

Our results showed that the EMD, the PT, and the RFD were not significantly affected by graft choice (BTB vs QT). However, the EMD was significantly longer for repetition 3

compared with repetition 2 on the operative limb of the VL (MD, 16 milliseconds; $P = .039$) and the RF (MD, 17 milliseconds; $P = .042$). Additionally, the RF produced significantly longer EMD on the operative versus the nonoperative limb (MD, 24 milliseconds; $P = .004$). The PT for repetition 1 was significantly higher than for repetition 2 (MD, 8.52 N·m; $P = .001$) and repetition 3 (MD, 7.79 N·m; $P = .031$). Last, the RFD was significantly slower for repetition 1 than for repetition 2 (MD, −20.46 N·m/s; $P = .039$) and 3 (MD, −29.85 N·m/s; $P = .002$) and was

significantly slower for the operative versus the nonoperative limb (MD, 23.7 N·m/s; $P = .034$).

Our finding that graft location choice did not significantly affect the EMD did not support our hypothesis that the EMD would be longer in the superficial quadriceps muscles of the operative limb when utilizing the QT graft compared with the BTB graft; however, our results showing longer RF EMD and VL EMD are supported by a number of studies that used diverse grafts. Kaneko et al²⁵ reported an ≈ 20 -millisecond difference between the operative and nonoperative limbs of their ACLR group 2 to 3 months after surgery, which was comparable with the differences in RF EMD and VL EMD values between the operative and nonoperative limbs in our sample. Similarly, Freddolini et al¹⁴ reported significantly longer EMD for the semitendinosus of the operative compared with the nonoperative limb 2 years after ACLR using the semitendinosus tendon. Finally, in partial agreement with our findings, Georgoulis et al¹⁶ reported no significant differences between EMD values of the VM and the RF for the operative versus the nonoperative limb measured approximately 10 and 45 months after BTB ACLR.

The longer EMD for the third repetition compared with the second repetition in the VL and the RF on the operative limb, as well as the longer RF EMD for repetition 3 on the operative compared with the nonoperative limb, partially supported the hypothesis that there would be greater increases in the EMD for the RF compared with the VM and the VL. The delay observed in repetition 3 was likely because of greater fatigue over the course of the 3 repetitions on the operative limb. Similarly, in a sample of 12 patients with ACLR using quadruple hamstring grafts at 24 to 26 months after surgery, Ristanis et al³⁸ reported significantly longer EMD for the last 5 compared with the first 5 of 25 explosive isometric knee flexion contractions held for 8 seconds. This indicates that protraction in EMD of an ACLR operative limb may be observed in as few as 3 maximal 3-second contractions with 30-second intertrial recoveries.

The prolonged EMD seen in the operative limbs of our participants may have been attributable to reduced stiffness in the series and parallel elastic components of the muscles secondary to decreases in reduced collagen thickness²⁶ and shifts toward slow-twitch isoforms.²⁵ Additionally, the EMD may have been lengthened after ACLR because of reduced proprioception,^{30,33} impaired gamma loop function,³⁷ and degraded calcium handling²⁵ secondary to surgical damage and atrophy.

The effect of prolonged EMD on performance and injury potential has been well documented. Hannah et al²⁰ found that during explosive movements, the hamstrings EMD (44.0 milliseconds) was 95% longer than the quadriceps EMD (22.6 milliseconds). They noted that this longer hamstrings EMD impaired early phase explosive force production and could leave the knee unstable and vulnerable to ACL injury during this time period. Chen et al⁶ reported a longer EMD in the VM obliquus than the VL of patients with patellar femoral pain syndrome, which they suggested might contribute to inefficient patellar movement and abnormal patellar tracking.

The longer EMD by the third testing repetition for the RF and the VL of the operative limb in our participants may increase the likelihood of noncontact ACL reinjury.¹ The increased EMD in our patients' operative limb compared with the nonoperative limb, especially as it was associated with fatigue during the latter sets, in our opinion, may constitute a marker of increased risk for ACL injury.¹¹ Mechanistically, there is a critical time period between the initial stimulus, neural communication, and sufficient muscular support that allows movements to be properly executed. We therefore theorize that because of a delay in neuromuscular communication, the athlete could be at greater risk for injury even before the onset of fatigue further increases EMD.

The greater PT values obtained during repetition 1 compared with repetitions 2 and 3 may have been attributable to fatigue and appeared unrelated to either ACLR technique. Our findings are in partial agreement with a review of knee muscle strength recovery after QT in which Johnston et al²⁴ reported strength recovery to be incomplete at 24 months. Additionally, our results agree with those of Hunnicutt et al²³ who reported no differences in isometric or isokinetic strength recoveries 6 to 23 months after surgery. The PT is a commonly utilized measure to assess recovery status and return to play readiness after ACLR. Angelozzi et al¹ noted that recovery and readiness is determined by achieving 85% to 90% of the maximal strength of the nonoperative limb, a level clearly reached by the participants in the current study ($\approx 93\%$). However, as noted by Zwolski et al,⁴³ athletes who are able to return to their sports after ACLR are still at risk of reinjury, and 20% to 30% will undergo a second ACL injury. Quadriceps weakness has also been linked to asymmetric limb loading and decreased stability of the knee during functional activities.

Our results, showing longer RFD for the operative versus nonoperative limbs of our patients, are reflective of the findings of Kline et al²⁷ who reported longer RFD for the operative versus nonoperative limb of patients 6 months after BTB ACLR. Further, the longer RFD for repetitions 2 and 3 compared with repetition 1 may have been the result of potentiation induced by the first repetition.¹⁸ Despite the differences between the operative and nonoperative limbs observed in the PT and the RFD during the current study, graft location choice had no significant effect. The RFD is not simply a measure of the readiness to return to play but also is a measure of the likelihood of reinjury. Therefore, the somewhat prolonged RFD on the operative limb, especially for the first (30% increase) and the last repetitions (40% increase) when fatigue may have had a significant influence, may be clinically important in this population, especially as an RFD can reduce the probability of noncontact ACL injury.¹

While the exact mechanisms behind these findings are unknown, it appears that the strengths inherent to each autograft—the BTB having greater strength and stiffness and the QT having greater collagen content and a greater cross-sectional area—produced similar response in the RFD, the PT, and the RFD. Therefore, an informed decision on the appropriate graft location choice can be made specific to individuals' risk factors analysis.^{3,28}

While graft location choice did not affect the EMD, the PT, and the RFD, the effect of specific grafts on these factors requires further investigation, as it provides information that can affect orthopaedic decision making and postoperative rehabilitation.

Limitations

A number of limitations may have affected the results in this study. First, although the sample size was determined utilizing a power analysis program, the observed power was below the optimum for some interactions. Thus, an increase in sample size may lead to more significant findings. A second limitation was that the QT and BTB graft harvests performed by each surgeon were not consistent, which may have affected the results because of variations in the surgical technique. Third, variations in participants' activity levels and adherence to rehabilitation may have affected their performances on the tests. Fourth, the study incorporated a convenience sample; therefore, bias may have resulted because of patient selection. Fifth, although not statistically significant, Lysholm scores did differ between the QT and the BTB groups, which may have affected our results during voluntary isometric testing. And finally, our sample incorporated a larger number of men than women, although ACL injury risk was reported to be higher in the latter. The final 2 limitations may affect the generalizability of our results.

CONCLUSION

The present study demonstrated that the EMD, the RF, and the PT were not significantly different between BTB and QT groups, supporting the viability of both graft options for ACLR. Nevertheless, all variables were affected by ACLR, regardless of graft type. However, the current study evaluated neuromuscular variables only during isometric contractions, and evaluations were performed at >1 year after ACLR. Future longitudinal studies involving dynamic movements should be considered to investigate potential neuromuscular alterations. Further, the differences seen in the EMD, the RF, and the PT, their potential effect on performance, and return to sports and reinjury, as well as the low cost of these tests, indicate the potential importance of including these measures during postoperative and longer-term evaluations.

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