

Quadriceps Recovery After Anterior Cruciate Ligament Reconstruction With Quadriceps Tendon Versus Patellar Tendon Autografts

Jennifer L. Hunnicutt,^{*†} PhD, ATC, Chris M. Gregory,[‡] PhD, PT, Michelle M. McLeod,[§] PhD, ATC, Shane K. Woolf,^{||} MD, Russell W. Chapin,[¶] MD, and Harris S. Slone,^{||} MD

Investigation performed at the Medical University of South Carolina, Charleston, South Carolina, USA

Background: Quadriceps tendon (QT) autografts are being increasingly used for anterior cruciate ligament reconstruction (ACLR). A paucity of studies exist that compare QT autografts with alternative graft options. Additionally, concerns exist regarding quadriceps recovery after graft harvest insult to the quadriceps muscle-tendon unit.

Purpose/Hypothesis: The purpose of this study was to compare quadriceps recovery and functional outcomes in patients with QT versus bone-patellar tendon-bone (BPTB) autografts. The hypothesis was that those with QT autografts would demonstrate superior outcomes.

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

Methods: Active patients with a history of primary, unilateral ACLR with soft tissue QT or BPTB autografts participated. Quadriceps recovery was quantified using variables of strength, muscle size, and activation. Knee extensor isometric and isokinetic strength was measured bilaterally with an isokinetic dynamometer and normalized to body weight. Quadriceps activation was measured with the superimposed burst technique. The maximal cross-sectional area of each quadriceps muscle was measured bilaterally using magnetic resonance imaging. Assessors of muscle size were blinded to the graft type and side of ACLR. Functional tests included hop tests and step length symmetry during walking, measured via spatiotemporal gait analysis. Self-reported function was determined with the International Knee Documentation Committee (IKDC) questionnaire. Neuromuscular and functional outcomes were expressed as limb symmetry indices (LSIs: [surgical limb/nonsurgical limb]*100%). Wilcoxon rank-sum tests were used to compare the LSIs and IKDC scores between groups.

Results: There were 30 study participants (19 male, 11 female; median age, 22 years [range, 14-41 years]; median time since surgery, 8 months [range, 6-23 months]), with 15 patients in each group. There were no significant between-group differences in demographic variables or outcomes. LSIs were not significantly different between the QT versus BPTB group, respectively: knee extensor isokinetic strength at 60 deg/s (median, 70 [range, 41-120] vs 68 [range, 37-83]; $P = .285$), activation (median, 95 [range, 85-111] vs 92 [range, 82-105]; $P = .148$), cross-sectional area of the vastus medialis (median, 79 [range, 62-104] vs 77 [range, 62-95]; $P = .425$), single-leg hop test (median, 88 [range, 35-114] vs 77 [range, 49-100]; $P = .156$), and step length symmetry (median, 99 [range, 93-104] vs 98 [range, 92-103]; $P = .653$). The median IKDC scores between the QT and BPTB groups were also not significantly different: 82 (range, 67-94) versus 83 (range, 54-94); respectively ($P = .683$).

Conclusion: Patients with QT autografts demonstrated similar short-term quadriceps recovery and postsurgical outcomes compared with patients with BPTB autografts.

Keywords: anterior cruciate ligament; ACL reconstruction; rehabilitation; quadriceps tendon

The majority of patients in the United States who rupture their anterior cruciate ligament (ACL) elect for ACL reconstruction (ACLR).^{28,29} The concept of anatomic individualized ACLR is used by many orthopaedic surgeons to restore normal anatomy and theoretically optimize functional outcomes.¹² Graft choice is made based on a number of patient

characteristics and goals. Ultimately, the goal of ACLR is to reproduce native anatomy and function while minimizing donor site morbidity. Autografts are most often used for young, active patients, as studies have demonstrated decreased rerupture rates compared with allografts.¹⁵

Bone-patellar tendon-bone (BPTB) autografts have been extensively studied and have been called the “gold-standard” graft of choice.³¹ Disadvantages of this graft include the risk of patellar fractures, donor site morbidity, and patellofemoral pain after surgery.¹³ Additionally,

The Orthopaedic Journal of Sports Medicine, 7(4), 2325967119839786
DOI: 10.1177/2325967119839786
© The Author(s) 2019

This open-access article is published and distributed under the Creative Commons Attribution - NonCommercial - No Derivatives License (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits the noncommercial use, distribution, and reproduction of the article in any medium, provided the original author and source are credited. You may not alter, transform, or build upon this article without the permission of the Author(s). For article reuse guidelines, please visit SAGE's website at <http://www.sagepub.com/journals-permissions>.

BPTB autografts may predispose patients to the risk of knee osteoarthritis at a greater rate than other autograft types.^{2,27,36} Thus, these concerns provide a motive to continue the search for an optimal autograft.

The quadriceps tendon (QT) has been increasingly utilized as an alternative option.³³ The QT can be harvested with or without bone and offers a larger and stronger anatomic area from which to harvest the graft.³² Anatomic studies have revealed that the QT is thicker, longer, and wider^{7,38} with higher collagen levels, contributing to greater strength of the QT compared with the patellar tendon.¹⁰ Additionally, initial studies utilizing QT autografts have revealed decreased donor site morbidity and similar anterior knee stability when compared with BPTB autografts.^{9,16,19} This evidence provides reason to believe that QT autografts could result in enhanced early and long-term clinical and functional outcomes. An evaluation of the extensor mechanism in cadaveric samples found that the QT after harvest can withstand greater tensile loads than the intact patellar tendon.¹ However, no study to date has quantified the effects of QT autografts on quadriceps recovery and morphology, despite the strong prediction of muscle size to strength after ACLR with other autografts.^{17,34}

To improve the understanding of the effects of QT autografts on quadriceps recovery, the purpose of this study was to compare interlimb differences in neuromuscular (muscle size, strength, and activation), functional, and patient-reported outcomes in patients with QT and BPTB autografts. We primarily aimed to evaluate group differences in quadriceps morphology, as harvest of the QT directly involves the knee extensor complex. Evidence has shown that quadriceps muscles selectively atrophy when evaluated before and after ACLR.²¹ More specifically, the vastus medialis demonstrates severe atrophy²¹ and significantly contributes to knee extensor strength.¹⁷ Therefore, it was chosen as the primary outcome of the present study. The hypothesis was that those with QT autografts would demonstrate superior outcomes compared with BPTB autografts.

METHODS

Study Design

This was a cross-sectional study in which a convenience sample of patients identified with a history of ACLR was assessed for isokinetic and isometric knee extensor

strength, central activation of the quadriceps muscle, quadriceps muscle size, gait symmetry, hop distance, and self-reported knee function. Institutional review board approval was obtained for this study.

Participants

A total of 30 patients who had undergone primary ACLR were recruited based on the following inclusion criteria: (1) 14 to 55 years of age; (2) a history of unilateral, isolated ACLR (with or without concomitant meniscal injuries) within the past 6 months to 2 years; (3) a reconstructive procedure using ipsilateral autografts harvested from either the patellar or the quadriceps tendon; (4) ACLR performed by one of the fellowship-trained orthopaedic surgeons involved in this study; and (5) informed consent from the patient or legal guardian. Exclusion criteria for the study were (1) a history of lower extremity injuries or surgery, including ACL retears and revisions, within the past 6 months; (2) multiligament reconstruction; (3) inability to walk without assistance from an orthotic, a knee brace, or another person; (4) self-reported knee arthritis that would limit range of motion at the knee joint; (5) any contraindications to magnetic resonance imaging (MRI), such as metal implants, pacemakers, and claustrophobia, among others; and (6) pregnancy.

All grafts were chosen according to surgeon and patient preference based on numerous factors, including skeletal maturity, patellar tendon length, sport- or position-specific demands, cosmesis, and pre-existing anterior knee pain. All QT autografts were harvested without bone plugs via a minimally invasive technique, according to Slone et al.³² All BPTB autografts were harvested with bone plugs. All femoral tunnels were created via an independent medial portal drilling technique. For QT autografts, graft fixation was achieved with suspensory fixation on the femur, while the tibial side was fixed with either adjustable loop buttons or tie-over-post screws. For BPTB autografts, the femur was fixed with either interference screws or suspensory fixation, while the tibia was fixed with interference screws.

Neuromuscular Outcome Measures

Strength. Isometric and isokinetic strength of the knee extensors of both limbs was measured on an isokinetic dynamometer (Biodex Medical Systems). Before testing,

*Address correspondence to Jennifer L. Hunnicutt, PhD, ATC, Emory University School of Medicine, 1968 Hawks Lane, Suite 205, Atlanta, GA 30329, USA (email: jlhunni@emory.edu) (Twitter: @JL_Hunnicutt).

[†]Department of Orthopaedic Surgery, Emory University School of Medicine, Atlanta, Georgia, USA.

[‡]Department of Health Sciences and Research, College of Health Professions, Medical University of South Carolina, Charleston, South Carolina, USA.

[§]Department of Health and Human Performance, College of Charleston, Charleston, South Carolina, USA.

^{||}Department of Orthopaedics and Physical Medicine, College of Medicine, Medical University of South Carolina, Charleston, South Carolina, USA.

[¶]Department of Radiology and Radiological Science, College of Medicine, Medical University of South Carolina, Charleston, South Carolina, USA.

One or more of the authors has declared the following potential conflict of interest or source of funding: This study was supported by the South Carolina Clinical & Translational Research Institute, at the Medical University of South Carolina, through National Institutes of Health grants TL1 TR001451 and UL1 TR001450. This project was also supported by the National Athletic Trainers' Association Foundation Award (1617DGP005). S.K.W. has received educational support from Arthrex, MTF, Smith & Nephew, and Stryker; honoraria and hospitality fees from MTF; and consulting fees from MicroAire. H.S.S. has received educational support from Arthrex and Smith & Nephew and speaking fees from Arthrex. 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 Medical University of South Carolina Institutional Review Board for Human Research (Pro00064965).

each participant underwent a period of familiarization and warm-up consisting of submaximal knee extension contractions at 25%, 50%, and 75% of their perceived maximal effort. After familiarization, 3 maximal contractions were performed with participants positioned in the dynamometer with their hips flexed to 85° and knees flexed to 90°.²² The axis of the dynamometer was aligned with the knee joint axis of rotation, with the lever arm secured to the leg being tested proximal to the lateral malleolus. Stabilization in the dynamometer was maintained with straps across the chest, hips, and knees. Participants were asked to develop torque as hard and fast as possible, with verbal encouragement from the tester, to produce a maximal contraction lasting approximately 5 seconds, separated by a 60-second rest period. During isometric testing, a maximum voluntary isometric contraction (MVIC) was defined as the highest isometric torque achieved during a 100-millisecond epoch and normalized to body weight (N·m/kg). Isokinetic testing of concentric knee extensor and flexor strength was also performed bilaterally via 5 repetitions at angular velocities of 60 and 180 deg/s through full range of motion and using gravity correction.³⁵ Peak torque occurring during the 5 trials was identified and normalized to body weight.

Central Activation. Central activation was simultaneously assessed during isometric testing. After the skin was cleaned with alcohol pads, two 7 × 13-cm self-adhesive electrodes (Dura-Stick II; Chattanooga Group) were placed in a bipolar fashion using the vastus medialis configuration.²³ Ten-pulse train electrical stimulation was delivered during MVICs (approximately 2 seconds after the beginning of the MVIC) using a square wave stimulator (Model S88; Grass Technologies) and a stimulation isolation unit (Model SIU8T; Grass Technologies). A standard intensity of 150 V was utilized for all participants. During the submaximal isometric trials, the intensity of electrical stimulation was superimposed at 25%, 50%, and 75% of 150 V in an effort to familiarize participants with the sensation of electrical stimulation during testing. Other stimulation parameters included a 200-millisecond train of 10 stimuli, at 50 pps, with a pulse duration of 0.6 milliseconds and a 0.01-millisecond pulse delay. The stimulator and the dynamometer were interfaced with a personal computer through a commercially available hardware system (MP150; Biopac Systems). Data were sampled at 2000 Hz and analyzed using commercially available software (Acq-Knowledge 4.4; Biopac Systems). Central activation was determined with the superimposed burst (SIB) technique and calculated with the following equation:

$$\text{Central activation} = \frac{\text{MVIC}}{\text{MVIC} + \text{SIB}} \times 100\%$$

Cross-sectional Area. MRI was conducted to compare the maximal cross-sectional area (CSA) of each of the knee extensor muscles between the surgical and nonsurgical limbs of each patient. All imaging was performed at 3.0 T (Prisma; Siemens) using a large body coil. T1 axial fast spin imaging without fat saturation was performed on the bilateral thighs from the knee joint line to the proximal

subtrochanteric femur (repetition time, 626 milliseconds; echo time, 10 milliseconds; echo train length, 3; 5-mm slice thickness; 0.5-mm interslice gap; 40-cm field of view; matrix, 384 × 384; and total scan length, 36 cm). Muscle and nonmuscle tissue was readily differentiated based on the conspicuity of fat planes on T1 images, and the CSA of each of the quadriceps muscles was measured on all consecutive slices by drawing a free-hand region of interest using publicly available software (OsiriX). Once the slice with the maximal CSA was found, the respective CSA measurement was averaged with that of the 2 adjacent slices and used in data analysis. This was done for each of the quadriceps muscles. All images were analyzed by 2 evaluators blinded to the graft type and side of surgery. Interrater reliability was determined to be excellent (intraclass correlation coefficient, 0.914; 95% CI, 0.823-0.959).

Functional Outcome Measures

Spatiotemporal Gait Analysis. Participants walked over a 14 ft-long portable walking system (GAITRite; CIR Systems) for 3 trials at their self-selected walking speed. They were not permitted to use any assistive devices or braces during trials. Step lengths for each limb were averaged by the system for each trial. The step lengths were then averaged across the 3 trials, and step length symmetry was calculated by dividing the step length of the surgical limb by that of the nonsurgical limb.

Hop Testing. Dynamic knee function was measured via hop tests (single-leg and crossover hop tests). Hop tests were conducted on the uninvolved limb first, followed by the involved limb. These tests have been determined to be safe, reliable, and valid measures of function in patients after ACLR.²⁴ The single-leg hop test was performed with the participant standing on one leg behind a marked starting line and performing one hop as far as possible. For the crossover hop test, the participant stood on one leg and hopped forward as far as possible 3 times while alternately crossing over a marked strip on the floor. For a trial to be considered successful, the participant must have landed on the tested limb in a controlled manner. The test was repeated if landing was not stable or if the contralateral limb touched the ground. The hop distance was measured to the nearest centimeter from the starting line to the participant's heel with a standard tape measure. Three successful trials were averaged and used in analyses.

Patient-Reported Outcome Measures

Participants completed the International Knee Documentation Committee (IKDC),¹⁴ Lysholm,²⁰ and Knee injury and Osteoarthritis Outcome Score (KOOS)²⁵ questionnaires. Each of the 5 KOOS subscales was analyzed individually.

Statistical Approach

Sample Size Estimation. The sample size was determined a priori for a simultaneous study conducted by our team. In patients with QT autografts, we aimed to test

interlimb differences in the primary outcome of CSA of the vastus medialis. This estimation was based on previous work by Thomas et al,³⁴ who investigated the CSA 6 months after ACLR with BPTB autografts. With an alpha level of .05, a total of 13 participants were needed to achieve 80% power and detect significant differences between limbs. An additional 2 participants were recruited to maximize attrition, totaling 15 participants. We also recruited 15 patients with BPTB autografts for comparison. Although we recognize that we were not sufficiently powered to determine differences between groups (see the Limitations section), these sample size numbers are comparable with other MRI studies after ACLR.^{3,37}

Statistical Analysis. Neuromuscular and functional outcomes were expressed as limb symmetry indices (LSIs; percentage of the surgical limb over the nonsurgical limb). Because of the relatively small sample size, it was determined a priori that only nonparametric statistical tests were to be used for all comparisons. More specifically, the Mann-Whitney *U* (Wilcoxon rank-sum) test was used to compare demographic variables, LSIs, and patient-reported outcomes between QT and BPTB groups. Data are reported as medians and ranges. All analyses were performed using SPSS Statistics 24 (IBM).

RESULTS

Demographic data are presented in Table 1. There were no significant differences between the groups for any demographic variables. Both groups were considered active, as evidenced by the Tegner activity level scores (Table 1). The majority of participants (67%) had returned to physical activity with no self-reported restrictions. Self-reported reasons for not returning to full physical activity included lack of time, fear, and sport participation being undesired or no longer relevant (eg, graduation from college). The QT group did have more male patients than the BPTB group, although this difference was not statistically significant ($\chi^2 = 3.59$, $P = .058$). Sex-based bias was limited by comparing interlimb differences rather than raw surgical limb values.

There were no significant differences between the groups for any neuromuscular or functional LSIs (Table 2). Additionally, there were no significant differences between the groups for patient-reported outcomes (Table 3).

DISCUSSION

The purpose of this study was to evaluate quadriceps recovery via neuromuscular, functional, and patient-reported outcomes in patients who had undergone ACLR with QT or BPTB autografts. The hypothesis that QT autografts would show superior outcomes was not supported by the results: LSIs of neuromuscular or functional outcomes in those with QT autografts were not significantly different from those with BPTB autografts. Additionally, patient-reported outcomes were not significantly different between the groups. Based on the results of this study, surgeons should feel comfortable performing ACLR with either QT

TABLE 1
Demographic Data^a

	QT Group (n = 15)	BPTB Group (n = 15)	<i>P</i>
Sex, male/ female, n	12/3	7/8	.058
Age, y	25.0 (14.0-41.0)	18.0 (15.0-32.0)	.389
Height, cm	175.3 (157.5-195.6)	172.7 (153.7-190.5)	.217
Weight, kg	81.4 (37.4-104.7)	73.9 (49.0-120.2)	.512
Body mass index, kg/m ²	24.3 (14.8-32.3)	23.6 (19.1-40.3)	.806
Time since surgery, mo	8.0 (6.0-23.0)	7.0 (6.0-21.0)	.653
Preinjury Tegner score	9 (6-10)	9 (3-10)	.775
Postoperative Tegner score	6 (4-9)	8 (3-9)	.389

^aData are reported as median (range) unless otherwise indicated. BPTB, bone–patellar tendon–bone; QT, quadriceps tendon.

TABLE 2
Neuromuscular and Functional Outcomes (in LSIs)^a

	QT Group	BPTB Group	<i>P</i>
Neuromuscular outcomes			
Knee extensor MVIC	62.8 (41.5-119.9)	58.8 (39.7-84.8)	.267
Isokinetic strength at 60 deg/s	69.9 (40.9-119.9)	67.8 (36.9-83.4)	.285
Isokinetic strength at 180 deg/s	77.7 (27.1-106.4)	69.5 (42.1-100.3)	.653
Activation	94.7 (85.3-110.7)	91.9 (81.7-104.8)	.148
CSA of vastus medialis	79.0 (62.3-103.7)	77.4 (62.1-95.1)	.425
CSA of vastus lateralis	84.5 (62.6-99.1)	78.4 (58.8-92.0)	.193
CSA of vastus intermedius	84.6 (63.2-99.2)	79.8 (63.1-102.8)	.561
CSA of rectus femoris	85.0 (77.7-110.2)	90.3 (81.7-112.1)	.400
Functional outcomes			
Single-leg hop test	87.6 (34.6-113.6)	77.1 (48.9-99.6)	.156
Crossover hop test	88.2 (58.1-116.1)	78.6 (41.0-103.9)	.256
Step length symmetry	98.8 (92.8-104.1)	98.3 (91.6-103.4)	.653

^aData are reported as median (range) in percentages. There were no significant differences between groups. BPTB, bone–patellar tendon–bone; CSA, cross-sectional area; LSI, limb symmetry index; MVIC, maximum voluntary isometric contraction; QT, quadriceps tendon.

or BPTB autografts, depending on which autograft they are most familiar with.

Research on QT autografts has been steadily increasing over the past 2 decades and continues to show the QT as a viable graft option for ACLR, particularly compared with the gold-standard BPTB graft.³³ Early studies have shown promise, with the present study contributing new findings on the QT that result in similar outcomes to the BPTB autograft.

TABLE 3
Patient-Reported Outcomes^a

	QT Group	BPTB Group	P
IKDC	81.6 (67.1-94.3)	82.8 (54.0-94.3)	.683
Lysholm	85.0 (75.0-100.0)	86.0 (74.0-100.0)	.468
KOOS-Pain	88.9 (72.2-100.0)	88.9 (69.4-100.0)	.389
KOOS-Symptoms	82.1 (39.2-96.4)	78.6 (42.9-96.4)	.870
KOOS-Activities of Daily Living	97.1 (76.5-100.0)	97.1 (89.7-100.0)	.870
KOOS-Sports	75.0 (55.0-100.0)	75.0 (45.0-90.0)	.267
KOOS-Quality of Life	62.5 (18.8-93.8)	68.8 (50.0-93.8)	.713

^aData are reported as median (range). There were no significant differences between groups. BPTB, bone-patellar tendon-bone; IKDC, International Knee Documentation Committee; KOOS, Knee injury and Osteoarthritis Outcome Score; QT, quadriceps tendon.

This is one of the first studies to describe and compare imaging and functional outcomes in patients with QT autografts. Quadriceps morphology is a critical variable to evaluate, as harvest of the QT involves direct alteration to the knee extensor complex. In the present study, LSIs of the CSAs of quadriceps muscles were not statistically different between the QT and BPTB groups. As expected and consistent with other work,²¹ the LSI of the vastus medialis was most severe (>20%) compared with other quadriceps muscles, but limb symmetry was not different between the groups. The CSA of quadriceps muscles after ACLR with QT autografts has been reported in only 1 other study in which the CSA increased after eccentric strength training.⁶ LSIs in that study were 82% to 84% for CSAs of quadriceps muscles, which are similar to values in our study. It should be noted, however, that comparing graft types was not the primary aim of that study. Secondary analysis of graft types (QT and hamstring tendon autografts) did not affect results.⁶ Interestingly, we studied each of the quadriceps muscles and found varying amounts of limb symmetry between muscles (ie, limb symmetry in rectus muscles was higher than in vastus muscles). This certainly warrants further investigation. Although more work is needed, early results are promising: even though part of the QT has been harvested, the resultant quadriceps CSA was similar to other autograft types.

Another critical variable to evaluate was central activation, which is a measure of the proportion of the quadriceps motor neuron pool that can be volitionally activated and is a contributing factor in diminished force production after ACLR.¹³ It has also been related to avoidance patterns during gait, patient-reported knee function, and quality of life.²² Although there were no significant differences between the groups, the QT group achieved what is considered to be normal activation ($\geq 95\%$).¹¹

Functional outcomes after ACLR with QT autografts have been scarcely reported in the literature. In the present study, we measured hop test performance and step length symmetry and found no differences between the groups. Tests of strength using isokinetic dynamometry have been more commonly reported. Similar to the results of the

present study, Han et al⁹ found no significant differences between the QT and BPTB groups for isokinetic knee extensor strength at 2-year follow-up after ACLR. Patient-reported outcomes, while still scarcely reported, have been more frequently compared between QT and BPTB groups, showing similar results to those in the present study with no significant differences for Lysholm,⁸ IKDC,^{9,16,19} or KOOS scores.¹⁹

Patients with hamstring tendon autografts were not included in the present study, but similar results have been reported when comparing hamstring tendon with QT autografts. At a 2-year postsurgical time point, there were no differences between the groups for Tegner, Lysholm, or visual analog scale scores.²⁶ Cavaignac et al⁴ found that QT autografts showed statistically better KOOS and knee stability scores, while anterior knee pain levels and isokinetic knee strength (extensor and flexor) were similar compared with hamstring tendon autografts. Lee et al¹⁸ also found no differences in knee extensor strength between groups but did find significantly greater knee flexor strength in the QT group. The ability to preserve knee flexor strength with QT autografts compared with hamstring tendon autografts may play a protective role in preventing reruptures of the ACL by providing increased stability at the knee joint.

Rehabilitation guidelines for patients with QT autografts are scarce. Given the current knowledge, rehabilitation should remain relatively similar to that with BPTB autografts, but there is room for improvement. Despite finding no significant differences in outcomes between the groups, patients with QT autografts still had significant deficits between limbs. Most notably, quadriceps size and strength were less in the reconstructed limb, even 10 months after surgery. Further work is needed to optimize recovery through maximizing the use of quadriceps muscles, no matter the autograft type. Because biomechanical studies have revealed that the QT autograft is stronger,^{1,10,30} with a greater CSA,³⁰ than the BPTB autograft, it is possible that the quadriceps of patients with QT autografts can be pushed harder and earlier without fear of compromising the healing graft. The additional preservation of knee flexor strength⁵ with QT autografts compared with hamstring tendon autografts may allow for greater knee joint stability while aggressively strengthening the quadriceps muscles earlier after surgery. Future work should focus on improving rehabilitation for patients with QT autografts to optimize quadriceps muscle outcomes and functional performance.

Limitations

This study is not without limitations. Primarily, the study design is a limitation, as we were not able to collect presurgical data or control for access and compliance to rehabilitation. This was a study of convenience sampling; therefore, the range of time since surgery is quite varied. However, all patients were at least 6 months postsurgery, and there was no significant difference between the groups for time since surgery. We recognize that a between-group difference in time since surgery of 1 month could be

clinically meaningful, but because of the small sample size, we were unable to control for time since surgery in analyses. This is a limitation and will be considered in larger studies. Other limitations are not including laxity measurements, lack of 2-year follow-up, and limited data on return to sport/activity. Although not statistically different, the percentage of male and female patients in each group was not balanced. To account for this, appropriate methods were undertaken to limit sex bias in the outcome measures. These methods included comparing interlimb differences rather than raw values.

Additionally, we recognize that we were likely not sufficiently powered to detect differences between the groups. According to the data of the present study, the effect size of the vastus medialis (primary outcome variable) was calculated at 0.75 (Cohen d). At an alpha level of .05 and 80% power, we would have needed 29 participants per group to detect a statistical significance in this variable in future studies. (Note that the sample size estimation of the current study was based on between-limb differences, not between-group differences.) Effect sizes were small to moderate for isometric strength ($d = 0.33$), isokinetic strength at 60 and 180 deg/s ($d = 0.38$), single-leg and crossover hop tests ($d = 0.36$ and 0.57 , respectively), and step length symmetry ($d = 0.22$), which indicate that larger sample sizes would be needed to detect significant differences between the groups. The effect size was extremely small for activation ($d = 0.08$). Future studies should include more rigorous designs (ie, randomized controlled trials) to longitudinally assess both the early changes and long-term outcomes of the QT autograft compared with the BPTB or other autografts.

CONCLUSION

This study demonstrated that the use of QT autografts in ACLR resulted in similar neuromuscular, functional, and patient-reported outcomes compared with BPTB autografts. As the BPTB is considered the gold-standard autograft, the results of this study, in addition to previous work, provide evidence for the QT as a viable autograft option for ACLR. Further work on earlier and longer term clinical outcomes will help clinicians to feel even more confident in the use of QT autografts for ACLR.

ACKNOWLEDGMENT

The authors thank Jenn Newton, DPT, and Kelli Adams, ATC, for their assistance with data collection and analysis of CSAs on MRI.

REFERENCES

- 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.
- Anderson MJ, Browning WM 3rd, Urband CE, Kluczynski MA, Bisson LJ. A systematic summary of systematic reviews on the topic of the anterior cruciate ligament. *Orthop J Sports Med*. 2016;4(3):2325967116634074.
- Arangio GA, Chen C, Kalady M, Reed JF 3rd. Thigh muscle size and strength after anterior cruciate ligament reconstruction and rehabilitation. *J Orthop Sports Phys Ther*. 1997;26(5):238-243.
- Cavaignac E, Coulin B, Tscholl P, Nik Mohd Fatmy N, Duthon V, Menetrey J. Is quadriceps tendon autograft a better choice than hamstring autograft for anterior cruciate ligament reconstruction? *Am J Sports Med*. 2017;45(6):1326-1332.
- Fischer F, Fink C, Herbst E, et al. Higher hamstring-to-quadriceps isokinetic strength ratio during the first post-operative months in patients with quadriceps tendon compared to hamstring tendon graft following ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(2):418-425.
- Friedmann-Bette B, Proft F, Gwechenberger T, et al. Strength training effects on muscular regeneration after ACL reconstruction. *Med Sci Sports Exerc*. 2018;50(6):1152-1161.
- Fulkerson JP, Langeland R. An alternative cruciate reconstruction graft: the central quadriceps tendon. *Arthroscopy*. 1995;11(2):252-254.
- Gorschewsky O, Klakow A, Putz A, Mahn H, Neumann W. Clinical comparison of the autologous quadriceps tendon (BQT) and the autologous patella tendon (BPTB) for the reconstruction of the anterior cruciate ligament. *Knee Surg Sports Traumatol Arthrosc*. 2007;15(11):1284-1292.
- 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.
- 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.
- Hart JM, Pietrosimone B, Hertel J, Ingersoll CD. Quadriceps activation following knee injuries: a systematic review. *J Athl Train*. 2010;45(1):87-97.
- Hofbauer M, Muller B, Murawski CD, van Eck CF, Fu FH. The concept of individualized anatomic anterior cruciate ligament (ACL) reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2014;22(5):979-986.
- Ingersoll CD, Grindstaff TL, Pietrosimone BG, Hart JM. Neuromuscular consequences of anterior cruciate ligament injury. *Clin Sports Med*. 2008;27(3):383-404.
- Irrgang JJ, Anderson AF, Boland AL, et al. Development and validation of the International Knee Documentation Committee subjective knee form. *Am J Sports Med*. 2001;29(5):600-613.
- Kaeding CC, Aros B, Pedroza A, et al. Allograft versus autograft anterior cruciate ligament reconstruction: predictors of failure from a MOON prospective longitudinal cohort. *Sports Health*. 2011;3(1):73-81.
- 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.
- Kuenze CM, Blemker SS, Hart JM. Quadriceps function relates to muscle size following ACL reconstruction. *J Orthop Res*. 2016;34(9):1656-1662.
- Lee JK, Lee S, Lee MC. Outcomes of anatomic anterior cruciate ligament reconstruction: bone-quadriceps tendon graft versus double-bundle hamstring tendon graft. *Am J Sports Med*. 2016;44(9):2323-2329.
- Lund B, Nielsen T, Fauno P, Christiansen SE, Lind M. Is quadriceps tendon a better graft choice than patellar tendon? A prospective randomized study. *Arthroscopy*. 2014;30(5):593-598.
- Lysholm J, Gillquist J. Evaluation of knee ligament surgery results with special emphasis on use of a scoring scale. *Am J Sports Med*. 1982;10(3):150-154.
- Norte GE, Knaus KR, Kuenze C, et al. MRI-based assessment of lower extremity muscle volumes in patients before and after ACL reconstruction. *J Sport Rehabil*. 2018;27(3):201-212.

22. Pietrosimone BG, Lepley AS, Ericksen HM, Gribble PA, Levine J. Quadriceps strength and corticospinal excitability as predictors of disability after anterior cruciate ligament reconstruction. *J Sport Rehabil.* 2013;22(1):1-6.
23. Pietrosimone BG, Selkow NM, Ingersoll CD, Hart JM, Saliba SA. Electrode type and placement configuration for quadriceps activation evaluation. *J Athl Train.* 2011;46(6):621-628.
24. Reid A, Birmingham TB, Stratford PW, Alcock GK, Giffin JR. Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. *Phys Ther.* 2007;87(3):337-349.
25. Roos EM, Roos HP, Ekdahl C, Lohmander LS. Knee injury and Osteoarthritis Outcome Score (KOOS): validation of a Swedish version. *Scand J Med Sci Sports.* 1998;8(6):439-448.
26. Runer A, Wierer G, Herbst E, et al. There is no difference between quadriceps- and hamstring tendon autografts in primary anterior cruciate ligament reconstruction: a 2-year patient-reported outcome study. *Knee Surg Sports Traumatol Arthrosc.* 2018;26(2):605-614.
27. Sajovic M, Vengust V, Komadina R, Tavcar R, Skaza K. A prospective, randomized comparison of semitendinosus and gracilis tendon versus patellar tendon autografts for anterior cruciate ligament reconstruction: five-year follow-up. *Am J Sports Med.* 2006;34(12):1933-1940.
28. Sanders TL, Maradit Kremers H, Bryan AJ, et al. Incidence of and factors associated with the decision to undergo anterior cruciate ligament reconstruction 1 to 10 years after injury. *Am J Sports Med.* 2016;44(6):1558-1564.
29. Sanders TL, Maradit Kremers H, Bryan AJ, et al. Incidence of anterior cruciate ligament tears and reconstruction: a 21-year population-based study. *Am J Sports Med.* 2016;44(6):1502-1507.
30. Shani RH, Umpierez E, Nasert M, Hiza EA, Xerogeanes J. Biomechanical comparison of quadriceps and patellar tendon grafts in anterior cruciate ligament reconstruction. *Arthroscopy.* 2016;32(1):71-75.
31. Shelton WR, Fagan BC. Autografts commonly used in anterior cruciate ligament reconstruction. *J Am Acad Orthop Surg.* 2011;19(5):259-264.
32. Slone HS, Ashford WB, Xerogeanes JW. Minimally invasive quadriceps tendon harvest and graft preparation for all-inside anterior cruciate ligament reconstruction. *Arthrosc Tech.* 2016;5(5):e1049-e1056.
33. 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.
34. Thomas AC, Wojtys EM, Brandon C, Palmieri-Smith RM. Muscle atrophy contributes to quadriceps weakness after ACL reconstruction. *J Sci Med Sport.* 2016;19(1):7-11.
35. Undheim MB, Cosgrave C, King E, et al. Isokinetic muscle strength and readiness to return to sport following anterior cruciate ligament reconstruction: is there an association? A systematic review and a protocol recommendation. *Br J Sports Med.* 2015;49(20):1305-1310.
36. Vairo GL, McBrier NM, Miller SJ, Buckley WE. Premature knee osteoarthritis after anterior cruciate ligament reconstruction dependent on autograft. *J Sport Rehabil.* 2010;19(1):86-97.
37. Williams GN, Buchanan TS, Barrance PJ, Axe MJ, Snyder-Mackler L. Quadriceps weakness, atrophy, and activation failure in predicted noncopers after anterior cruciate ligament injury. *Am J Sports Med.* 2005;33(3):402-407.
38. Xerogeanes JW, Mitchell PM, Karasev PA, Kolesov IA, Romine SE. Anatomic and morphological evaluation of the quadriceps tendon using 3-dimensional magnetic resonance imaging reconstruction: applications for anterior cruciate ligament autograft choice and procurement. *Am J Sports Med.* 2013;41(10):2392-2399.