Comparison of Short-term Biodex Results After Anatomic Anterior Cruciate Ligament Reconstruction Among 3 Autografts

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Background: An individualized approach to anterior cruciate ligament reconstruction (ACLR) typically includes criteria-based postoperative rehabilitation. However, recent literature has suggested residual quadriceps weakness up to 12 months after ACLR, especially with a quadriceps tendon (QT) autograft.

Hypothesis: The QT would have poorer quadriceps strength symmetry at 5 to 8 months compared with the hamstring tendon (HS) and patellar tendon (BPTB), but there would be no significant difference at 9 to 15 months among all 3 groups.

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

Methods: Patients who underwent anatomic primary ACLR with an autograft were reviewed retrospectively. Isometric quadriceps and hamstring strength measurements were obtained clinically at 5 to 8 months and 9 to 15 months postoperatively. Return-to-running and return-to-play criteria included greater than 80% and 90% quadriceps strength symmetry, respectively.

Results: A total of 73 patients with 5- to 8-month follow-up were identified, and 52 patients had 9- to 15-month data. The QT group had a significantly lower quadriceps index at 5 to 8 months (69.5 ± 17.4) compared with the BPTB (82.8 ± 14.6; $P = .014$) and the HS (86.0 ± 18.6; $P = .001$) groups. More patients with an BPTB autograft met criteria for return to running and return to play (60% and 47%, respectively) compared with the QT group (26% and 13%, respectively) at 5 to 8 months. Given the sample sizes available, we observed no significant difference in the quadriceps index and return-to-play and return-to-running criteria at 9 to 15 months among those undergoing ACLR with a QT, BPTB, or HS graft.

Conclusion: Patients undergoing ACLR with a QT graft demonstrated clinically meaningful quadriceps asymmetry at 5 to 8 months and 9 to 15 months postoperatively. Additionally, fewer patients in the QT group met criteria for return to play and running at 5 to 8 months than the BPTB and HS groups. These data suggest that a longer time to return to play and specific rehabilitation protocols that emphasize quadriceps strengthening may be necessary because of residual quadriceps weakness after ACLR with a QT graft.

Keywords: ACL; quadriceps index; quadriceps tendon; return to play; weakness

Rates of return to competitive sports are poor after anterior cruciate ligament reconstruction (ACLR), with reported rates as low as 55%.[3,4,7] To improve on this poor return, an individualized approach to ACLR has recently been advocated, which includes consideration of patient activity level and preference, anatomic ACLR, and use of criteria-based postoperative rehabilitation.[27,28,43,52]

Anatomic ACLR can be performed with an allograft or autograft, and the ultimate choice of graft should be made considering the advantages and disadvantages of each with respect to the patient's goals and preferences. Autograft options for ACLR include the patellar tendon (BPTB), hamstring tendon (HS), and quadriceps tendon (QT). Although the BPTB is still considered the gold standard by most orthopaedic surgeons,[13] a recent survey demonstrated that 53.1% of surgeons preferred the HS, while only 22.8% chose the BPTB.[37] Interestingly, more surgeons preferred an allograft (13.5%) than the QT (10.6%), even as recent literature has raised concerns related to the failure rate of ACLR when performed with an allograft.[37,40]

Each graft has unique advantages and disadvantages. BPTB grafts have been associated with difficulty in kneeling,[32] anterior knee pain,[20,24,38,41] risk of patellar fractures,[14,42] quadriceps weakness, and risk of radiographic osteoarthritis within the patellofemoral joint.[31,41] HS grafts have fewer harvest-site complications and demonstrate excellent long-term outcomes[41] but have been shown to have greater failure rates, greater laxity on clinical examination, theoretical risk of dynamic valgus instability, radiographic osteoarthritis within the patellofemoral joint,

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and persistent hamstring weakness.[5,6,8,10,11] QT grafts have recently gained popularity, as there is no risk of hamstring weakness and less risk of anterior knee pain and patellar fractures (when a bone block is not utilized).[18,26,30,38,48] However, various studies have suggested initial quadriceps weakness, with a reported 85% recovery of quadriceps power at 3 years.[24,33]

The ideal return-to-play criteria are still controversial, especially for elite athletes.[9,25] However, there is near-universal acknowledgment that quadriceps strength symmetry should be measured and considered when making return-to-sport decisions, among other criteria. The most recent literature recommends that patients can return to activities once quadriceps strength reaches 90% symmetry of the contralateral side.[1,16,34,35,49,55] Studies of return to sports in elite soccer and football have reported that 63% to 94% of elite athletes return to play within 12 months of ACLR, with younger patients and male patients more likely to return.[12,45,53] Documented rates of return to competitive sports are less than 50% by 12 months in high school and collegiate athletes, suggesting that these patients may need longer postoperative rehabilitation. Additionally, although athletes have been able to return to play, 60% to 70% reported an inability to achieve their preinjury level of play.[7,36] Most of these studies, however, suggested that graft choice did not have an effect on return to play or did not specifically compare different graft options.

There is a paucity of literature directly comparing short-term strength outcomes of a QT graft with all other autograft types after anatomic ACLR. Therefore, the purpose of this study was to compare short-term quadriceps and hamstring strength outcomes within the return-to-play time frame among the BPTB, QT, and HS after anatomic primary ACLR. We hypothesized that QT grafts would have poorer quadriceps strength symmetry at 5 to 8 months compared with HS and BPTB grafts but that there would be no significant difference at 9 to 15 months among all 3 groups. Additionally, we hypothesized that HS grafts would demonstrate significant hamstring weakness at 5 to 8 months and 9 to 15 months compared with QT and BPTB grafts.

METHODS

Patient Selection

We reviewed the charts of all patients who presented to the UPMC Rooney Sports Complex with a primary ACL injury from 2010 to 2015. Inclusion criteria included primary ACLR with an autograft and documented postoperative isometric strength measurements utilizing a System 3 electromechanical dynamometer (Biodex Medical Systems). Exclusion criteria included ACLR with an allograft, meniscal repair, incomplete or inadequate postoperative isometric strength measurement data, concomitant ligamentous knee injuries other than an ACL tear, history of contralateral ACL tears, revision ACLR, and prior distal femur or proximal tibial fractures. The University of Pittsburgh Institutional Review Board provided a waiver of informed consent for a retrospective review of existing clinical data.

Quadriceps and Hamstring Strength Testing

As a part of routine clinical care and/or research study participation after ACLR, patients completed isometric testing of their quadriceps and hamstring strength routinely throughout the postoperative period. We chose to implement isometric testing because of the noted learning curve associated with isokinetic testing. Visits were typically scheduled to coincide with surgeon follow-up visits throughout the duration of the postoperative period and were not standardized across patients. Along with other objective criteria (hop tests, tests of neuromuscular control, etc), isometric strength testing was used to determine if a patient was prepared for activity progression after surgery in our clinical practice. Generally, running was not permitted until 4 months after surgery, and initial strength tests did not occur until this time. Before testing, the patients performed a 10-minute cardiovascular warm-up that consisted of lower extremity strength and stretching exercises to minimize injuries and maximize testing accuracy.

To determine the strength profile in the late rehabilitation phase, we looked at the first available strength assessment in the 5- to 8-month time frame after surgery (eg, if a single patient underwent both 5- and 7-month postoperative assessments, only the 5-month time point was considered). To determine the strength profile in the return-to-play phase, we also considered the 9- to 15-month strength assessments.

To test quadriceps and hamstring strength, patients sat in the dynamometer with the hips flexed to 80° and the knee flexed to 60°. The axis of the dynamometer was aligned with the knee joint axis, and the dynamometer arm was fixed to the patient just above the ankle mortise. Straps

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Ethical approval for this study was obtained from the University of Pittsburgh Institutional Review Board (No. REN18050002/PRO12020619).

TABLE 1
Demographic Data[a]

	5- to 8-Month Follow-up			9- to 15-Month Follow-up		
	QT (n = 39)	BPTB (n = 15)	HS (n = 19)	QT (n = 29)	BPTB (n = 10)	HS (n = 13)
No. of male patients	25	10	6	15	8	6
Age, mean (range), y	23 (15-45)	24 (17-44)	23 (15-31)	23 (15-45)	23 (17-34)	23 (16-32)
Days from surgery, mean ± SD (range)	186 ± 20 (139-222)	190 ± 28 (140-238)	177 ± 30 (139-244)	320 ± 59 (251-426)	321 ± 59 (253-413)	298 ± 47 (246-370)

[a]The HS group had significantly more female patients than the BPTB and QT groups at 5 to 8 months ($P = .042$), but there was no significant difference at 9 to 15 months ($P > .05$). There was no significant difference in age or time from surgery between the groups ($P > .05$). BPTB, patellar tendon; HS, hamstring tendon; QT, quadriceps tendon.

secured the pelvis and thigh of the testing limb to the seat for stabilization. Patients were instructed to utilize the hand grab bars on the seat for upper body fixation.[47]

The System 3 dynamometer provides automated administration. Patients alternated 5-second maximal contractions of the QT and HS with 30 seconds of rest between each contraction for 3 contractions of each muscle. Before maximal testing, patients completed submaximal (50% and 75% of maximum effort) and maximal effort contractions for familiarization with the testing procedures. During testing, testers provided verbal encouragement, and the dynamometer provided visual feedback. Maximal force output for the QT and HS of each limb was recorded for analysis.

Data Reduction and Statistical Analysis

To normalize strength outcomes among participants, we calculated the quadriceps index (QI) and hamstring index (HI) by expressing the involved limb's strength as a percentage of the uninvolved limb's strength. Therefore, values less than 100% indicated a strength deficit in the reconstructed limb, while values greater than 100% indicated greater strength in the reconstructed limb.

Common clinical benchmarks for assessing quadriceps strength include 80% symmetry for return to running and 90% symmetry for return to play.[1,39,49,54] Thus, for each case, we classified quadriceps strength symmetry in 2 ways: If a participant had a QI greater than 80%, they were indicated as "cleared for running," and if a participant had a QI greater than 90%, he or she was classified as "cleared for play." However, these data were not used in isolation when determining clearance for running and play but rather were combined with other objective criteria.

Patients were tested multiple times throughout their rehabilitation after ACLR. Each patient was tested by the same physical therapist throughout the duration of the postoperative period; however, multiple therapists performed the tests for the study population. Before dynamometer testing, all physical therapists familiarized themselves with the procedure, including computer operation, patient alignment, and verbal instructions for testing. Recommended rehabilitation guidelines were similar for all patients. All testing was completed at the UPMC Rooney Sports Complex; however, some patients performed their rehabilitation in other clinics. Therefore, the exact structure of rehabilitation sessions and the number of sessions completed were unknown.

Data were summarized with descriptive statistics and inspected for normality. Comparisons of quadriceps and hamstring strength among graft types were conducted with standard analysis of variance (ANOVA) and the post hoc Student t test. We used frequencies to summarize the numbers of participants who met the clinical criteria for return to running and return to play and compared the proportions with a chi-square test. Statistical significance was set at alpha = .05 a priori. All statistical analyses were conducted with Stata version 14.2 (StataCorp).

RESULTS

A total of 73 patients were identified at 5- to 8-month follow-up, and a separate cohort of 52 patients had 9- to 15-month data. Demographic data are listed in Table 1. For QT grafts, all were full-thickness grafts, and some had a bone block depending on surgeon preference. All HS grafts were double stranded, and muscles varied depending on surgeon preference. ANOVA demonstrated no significant differences in age or time from surgery among any of the groups at 5 to 8 months ($P = .7695$ and $P = .3066$, respectively) and 9 to 15 months ($P = .9753$ and $P = .4794$, respectively). At 5- to 8-month follow-up, the HS group had significantly more women than the BPTB or QT groups ($P = .042$), but no difference was found in the 9- to 15-month time period ($P > .05$).

QI and HI data are listed in Table 2. ANOVA demonstrated a significant difference in the QI and HI among the groups at 5 to 8 months ($P = .0016$ and $P = .0087$, respectively). The QT group had a significantly lower QI at 5 to 8 months (69.5 ± 17.4) compared with the BPTB (82.8 ± 14.6; $P = .014$) and HS (86.0 ± 18.6; $P = .001$) groups, but there was no difference in the QI between the BPTB and HS groups ($P = .591$). Similarly, the post hoc t test also revealed that the HS group had a significantly lower HI at 5 to 8 months (79.5 ± 14.6) compared with the BPTB group

TABLE 2
Quadriceps and Hamstring Indexes[a]

	5- to 8-Month Follow-up			9- to 15-Month Follow-up		
	QT (n = 39)	BPTB (n = 15)	HS (n = 19)	QT (n = 29)	BPTB (n = 10)	HS (n = 13)
QI, %	69.5 ± 17.4[b] (27.0-105.1)	82.8 ± 14.6 (54.5-104.5)	86.0 ± 18.6 (43.1-120.4)	83.3 ± 20.7 (42.6-142.8)	97.0 ± 13.8 (77.3-114.9)	90.9 ± 17.5 (67.1-121.6)
HI, %	88.4 ± 17.4 (64.0-138.6)	98.0 ± 17.5 (73.6-134.4)	79.5 ± 14.6[c] (36.5-100.4)	99.8 ± 20.1 (67.4-157.0)	99.6 ± 17.6 (78.9-134.0)	84.2 ± 23.1 (54.4-125.6)

[a]Data are reported as mean ± SD (range). At 5 to 8 months, the QI for the QT group was significantly lower compared with the BPTB (P = .014) and HS groups (P = .001), and the HI for the HS group was significantly lower compared with the BPTB group (P = .002) but not significantly different compared with the QT group (P = .062). At 9 to 15 months, there was no significant difference between the groups. Because of the small sample sizes in the assessment of the QI at 9 to 15 months, we were not adequately powered to indicate that there was no difference in the QI. BPTB, patellar tendon; HI, hamstring index; HS, hamstring tendon; QI, quadriceps index; QT, quadriceps tendon.
[b]Significant difference between QT and BPTB ($P < .05$) and between QT and HS ($P < .05$).
[c]Significant difference between HS and BPTB ($P < .05$).

TABLE 3
Return-to-Play and Return-to-Running Results[a]

	5- to 8-Month Follow-up			9- to 15-Month Follow-up		
	QT (n = 39)	BPTB (n = 15)	HS (n = 19)	QT (n = 29)	BPTB (n = 10)	HS (n = 13)
Return to play	5[b] (13)	7 (47)	5 (26)	10 (35)	7 (70)	6 (46)
Return to running	10[b] (26)	9[c] (60)	16 (84)	14 (48)	7 (70)	9 (69)

[a]Data are reported as n (%). For each case, we classified quadriceps strength symmetry in 2 ways: If a participant had a quadriceps index (QI) greater than 80%, he or she was indicated as "cleared for running," and if a participant had a QI greater than 90%, he or she was indicated as "cleared for play." There were significantly fewer patients in the QT group who met return-to-play criteria at 5 to 8 months compared with the BPTB and HS groups (P = .007 and $P < .001$, respectively). There were significantly fewer patients in the QT group who met return-to-running criteria at 5 to 8 months compared with the BPTB group (P = .0179). Because of the small sample sizes in the assessment of the QI at 9 to 15 months, we were not adequately powered to indicate that there was no difference in return-to-play and return-to-running criteria. BPTB, patellar tendon; HS, hamstring tendon; QT, quadriceps tendon.
[b]Significant difference between QT and BPTB ($P < .05$) and between QT and HS ($P < .05$).
[c]Significant difference between BPTB and QT ($P < .05$) and between BPTB and HS ($P < .05$).

(98.0 ± 17.5; P = .002) but no significant difference compared with the QT group (88.4 ± 17.4; P = .062).

At 9 to 15 months, ANOVA demonstrated no significant difference among the groups in quadriceps strength symmetry (P = .1229) or hamstring strength symmetry (P = .0609). However, post hoc power analysis indicated that we were not adequately powered to state definitively that there was no difference (60% achieved power for quadriceps symmetry and 40% for hamstring symmetry at 5-8 months and 50% at 9-15 months).

The results of the return-to-play and return-to-running criteria are listed in Table 3. The Pearson chi-square test indicated a significant difference in return-to-play and return-to-running criteria among all 3 groups at 5 to 8 months ($P < .001$ and P = .029, respectively). At 9 to 15 months, the Pearson chi-square test found no difference in return-to-play and return-to-running criteria among all 3 groups (P = .147 and P = .304, respectively). However, the QI data for the groups at 9 to 15 months were not adequately powered, and therefore, we cannot definitively state that there was no difference in return-to-play and return-to-running criteria.

DISCUSSION

After anatomic ACLR with a QT autograft, patients demonstrated significantly worse isometric quadriceps strength symmetry in the late rehabilitation phase; however, with the available sample size, we were unable to find a difference in the QI and return-to-play and return-to-running criteria at 9 to 15 months after surgery among those undergoing ACLR with a QT, BPTB, or HS graft. Expectedly, those undergoing ACLR using a HS autograft had a clinically relevant hamstring weakness at both time points. The study data also demonstrated that 87% of patients with a QT autograft did not have sufficient quadriceps strength symmetry to meet return-to-play criteria and that 74% did not have sufficient quadriceps strength symmetry to meet return-to-running criteria at 5 to 8 months based on the QI. Furthermore, a considerable number of patients in the QT and HS groups (65% and 54%, respectively) did not meet the quadriceps strength return-to-play criteria at 9 to 15 months postoperatively. These results indicate that there is a need to alter rehabilitation after ACLR with a QT autograft to maximize quadriceps strength symmetry and after ACLR with an HS autograft to maximize hamstring strength symmetry. This information may assist clinicians in educating patients about the rehabilitation necessary after ACLR depending on the graft chosen.

While the BPTB remains the gold standard graft for ACLR, many surgeons continue to utilize soft tissue grafts such as an HS autograft because of fewer donor-site complications,[30] less quadriceps weakness,[17,31] and higher tensile strength than a BPTB graft.[44] A histological cadaveric study demonstrated that the HS provides 20% to 30% more fibril/interstitium ratio and 35% to 50% more fibroblasts compared with the BPTB when assessing the longitudinal sections of entire tendons.[23] However, numerous studies have reported greater failure rates with HS grafts.[10,19] Recently, the QT autograft has gained popularity for various reasons. During harvest, a surgeon can obtain a graft of consistent length (7-8 cm), depth (6-7 mm), and width (9-10 mm) without the risk of violating the suprapatellar pouch.[15] Histologically, the thickness of the QT is 1.8 times that of the BPTB, contains 20% more collagen, and has twice the cross-sectional area of a BPTB of the same thickness.[26,46] However, residual quadriceps weakness after ACLR with a QT graft is a concern. A cadaveric study demonstrated that the tensile strength of the residual QT is reduced by approximately one-third after harvesting a partial-thickness 10 mm–wide graft. That study did conclude, that the postharvest strength of the residual QT is greater than that of the intact BPTB.[2] However, the data from our study were for full-thickness QT grafts, and no data were available for the now more commonly used partial-thickness QT grafts.

Various studies have documented good to excellent results for all 3 autograft types up to 10 years postoperatively,[20,41] but few have compared functional results among all 3 graft types. One study found that the QT group achieved full knee extension range of motion sooner than the BPTB group and required less pain medication than the BPTB and HS groups.[29] Han et al[24] demonstrated that quadriceps strength symmetry was poor at 6 months postoperatively in both the QT and BPTB groups but that quadriceps strength recovered to 74% and 78%, respectively, at 1 year postoperatively. A separate study looked solely at the QT and assessed quadriceps muscle power at 2- and 3-year follow-up after ACLR. The authors showed a mean 82% recovery at 2 years and 85% recovery at 3 years.[33]

The significant quadriceps weakness in the late rehabilitation phase in patients with a QT graft is of considerable interest, especially with regard to rehabilitation and return to sports. We chose to look at 2 time frames after ACLR based on the risk of second injuries and our clinical practice. Grindem et al[22] indicated that there is a protective effect of waiting until at least 9 months after surgery for returning to play, which was similar to the outcomes at our own institution.[50,51] They also showed that quadriceps strength deficit was a significant factor for knee reinjuries after return to sports, with a 3% reduced reinjury risk for every 1% increase in quadriceps strength symmetry. Additionally, within 9 months of ACLR, the reinjury rate was reduced by 51% with every 1-month delay in return to sports.[22] Therefore, we are especially concerned with quadriceps strength in the 5- to 8-month postoperative period as training intensifies and patients prepare to return to sports. Considering the demands of competition among other life demands of nonelite athletes (work, school, etc), time for training is limited, and strength training may not be emphasized appropriately.

The findings from this study indicate that current rehabilitation likely needs to be changed after ACLR with a QT graft because of persistent quadriceps weakness. A recent meta-analysis indicated that the current rehabilitation protocols after ACLR may not appropriately restore quadriceps strength and suggested that specific neuromuscular training should be added to training regimens to optimize rehabilitation protocols.[21] Along with this, it could be postulated that a reason for the increased failure rates of HS grafts may be premature return to sports and pivoting activities. Although 84% and 69% of the patients with HS grafts in the current study met return-to-running criteria at 5 to 8 and 9 to 15 months, respectively, only 26% and 46% met return-to-play criteria at 5 to 8 and 9 to 15 months.

Hamstring weakness is a well-documented sequela of ACLR with HS grafts.[4,6,8,11] The data from this study concur with current literature, demonstrating a 79.5% HI at 5 to 8 months and 84.2% HI at 9 to 15 months postoperatively. This may contribute to the reinjury risk, as injury prevention programs that emphasize eccentric hamstring strength and deceleration tend to improve injury risk profiles.[56]

This study has several limitations. This was a retrospective chart review of patients with available clinical strength data after ACLR. This does not represent all consecutive patients from our clinical practice. The chronicity of injury was not documented, which could affect the outcomes of these patients. Additionally, the timing of strength testing was not standardized but was scheduled to coincide with surgeon appointments for patients undergoing rehabilitation at other clinics. Clinical indications included progression of rehabilitation activities, subjective clinical improvement, and clearance for return to play and running. Consequently, fewer patients were available in the 9- to 15-month postoperative time, as they may have been discharged from physical therapy or self-discharged. As previously stated, this limited our statistical power for comparing quadriceps strength outcomes at 9 to 15 months. Because of the small sample sizes in the assessment of the QI at 9 to 15 months, we were not adequately powered to indicate that there was no difference in the QI.

Based on the available data comparing the 3 groups, we achieved a power of only 60%, indicating that there is a reasonable chance for stating that there is no difference when one actually exists. We would need at least 80 participants to achieve 80% power based on the observed data. Similarly, for comparisons of the HI, we achieved only 40% power at 5 to 8 months and 50% power at 9 to 15 months. Definitive comparisons of quadriceps recovery among autograft sources should be made in a prospective manner with larger sample sizes and smaller standardized testing windows. While all patients underwent surgery in the same center, rehabilitation protocols were surgeon specific but generally relied on the same return-to-sports criteria. Rehabilitation was conducted in many different clinics, and the details were not explicitly known.

CONCLUSION

Patients undergoing ACLR with a full-thickness QT autograft demonstrated significant isometric quadriceps weakness at 5 to 8 months postoperatively compared with BPTB and HS grafts, but with the available sample sizes, we were not able to find a significant difference among the groups at 9 to 15 months. The HS group exhibited significant hamstring weakness at 5 to 8 months compared with the QT group. Additionally, significantly fewer patients in the QT group met return-to-play criteria at 5 to 8 months compared with the BPTB and HS groups, and significantly fewer patients in the QT group met return-to-running criteria at 5 to 8 months compared with the BPTB group. With the available sample sizes, we were not able to find significant differences in return-to-play and return-to-running criteria at 9 to 15 months among all groups.

These data may assist clinicians and physical therapists when constructing postoperative protocols for patients after ACLR with a QT graft, as more intensive and isolated strengthening of the QT, longer time to return to play, and specific rehabilitation protocols may be necessary because of residual quadriceps weakness.

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