Original Article

Drop Vertical Jump Landing Mechanics Are Similar Between Patients With Quadriceps Tendon and Patellar Tendon Autografts After Anterior Cruciate Ligament Reconstruction

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Purpose: To compare the biomechanics of a drop vertical jump (DVJ) landing task and functional outcomes among patients with anterior cruciate ligament reconstruction (ACLR) with quadriceps tendon (QT) and patellar tendon (PT) autografts. **Methods:** Physically active patients who underwent primary ACLR with either a QT or PT autograft were included in this study. All were within 6 months to 2 years after surgery and cleared for return to physical activity. Subjects completed DVJs in a biomechanics laboratory. Peak vertical ground reaction force (VGRF) and lower-extremity joint sagittal and frontal plane kinematics and kinetics were collected and analyzed. Mann-Whitney *U* tests were used to compare the surgical limbs of the QT and PT autograft groups for kinematic and kinetic variables. Wilcoxon rank-sum tests were used to compare the surgical and nonsurgical limbs for both the QT and PT autograft groups. **Results:** Twenty-four physically active individuals who underwent primary ACLR with QT (n = 14) or PT (n = 10) autografts completed DVJs in a biomechanics laboratory. There were no statistically significant biomechanical differences between the QT and PT groups. Peak VGRF differed between the surgical and nonsurgical limbs for the QT (surgical and nonsurgical, 1.10 and 1.30 N) and PT (surgical and nonsurgical, 1.10 and 1.35 N) groups. Specifically, both groups demonstrated lower VGRFs in the surgical limb compared with the nonsurgical limb ($P < .05$). Additional medium and large effect sizes were found when comparing kinetic variables between limbs within both surgical groups. **Conclusions:** Regardless of the graft-specific surgical technique, patients who undergo ACLR are returning to activity with movements that resemble an offloading pattern of the surgical limb. Coupled with the finding of an absence of differences in kinematic and kinetic variables between the QT and PT autograft groups suggests that the QT graft may be a viable alternate graft source for ACLR. **Level of Evidence:** Level III, retrospective comparative study.

Anterior cruciate ligament (ACL) injuries have been approximated between 100,000 and 250,000 annually in the United States alone,[1-3] with an estimated 125,000 requiring anterior cruciate ligament reconstruction (ACLR) and rehabilitation.[4] Postsurgical recovery cost ranges from 11,500 to 17,000 dollars per patient[1,5] and more than $3 billion nationally in associated health care costs.[6] Despite surgery and rehabilitation to improve mechanical knee joint instability, ACL injuries result in increased risk of long-term disabilities and comorbidities, including increased risk of knee reinjury, knee osteoarthritis, and lower physical activity levels.[7,8]

Despite extensive scientific investigation, return to preinjury levels of activity after ACLR and the rate of subsequent knee surgeries are ongoing challenge[9]; therefore, the optimal graft choice for autograft ACLR continues to be controversial. For many surgeons, graft choice is made on the basis of the individual case, with consideration of the advantages and disadvantages of each type of graft, as well as the individual patient's goals and preferences.[10,11] Historically, graft options most commonly included patellar tendon (PT), hamstring tendon, or allograft tissue. However, autologous quadriceps tendon (QT) is increasing in

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popularity as a viable alternate source for ACLR.[10-12] On the basis of muscular strength outcomes[13,14] and movement analyses,[15] there is a growing body of evidence that shows the QT autograft has comparable outcomes with the PT autograft. Yet, few studies have evaluated the movement profile of individuals following ACLR with QT autografts.[14-16]

In studies of a drop vertical jump (DVJ) task in patients after ACLR with PT autografts, biomechanical variables associated with ACL reinjury relate to persistent alterations in lower-extremity landing mechanics.[17,18] Specifically, frontal plane knee range of motion during landing, asymmetries in sagittal plane knee moments at initial contact,[19] and increased vertical ground reaction forces[18] are all predictors of a second ACL injury. Further, a deficit in biomechanical variables on the surgical limb compared to the nonsurgical limb[20] is thought to negatively affect return to physical activity. This suggests that analyzing knee joint mechanics in ACLR patients is fundamental to better understanding the potential for future ACL injury and the individual's readiness for return to activity.

The purpose of this study was to compare the biomechanics of a DVJ landing task and functional outcomes among patients with ACLR with QT and PT autografts. We hypothesized that there would be no significant differences between the QT and PT groups in sagittal and frontal plane peak joint angles, peak joint forces, and vertical ground reaction forces (VGRFs) and also that the surgical limb would demonstrate significant biomechanical deficits compared with the nonsurgical limb in both groups.

Methods

Study Design

This cross-sectional study included patients who underwent primary ACLR with either all soft-tissue QT or PT autografts between 2015 and 2017. All participants completed a series of DVJs in the biomechanics laboratory during the study period, which occurred between 2017 and 2018. These data were collected as part of a larger investigation.[14] All individuals consented before participating in this study, which was approved by the institutional review board of The Medical University of South Carolina on April 30, 2017 (proposal # Pro00064965).

Participants

Patients were recruited from orthopaedic offices on the basis of the following criteria. Inclusion criteria included (1) age 14-55 years, (2) history of unilateral, isolated ACLR (with or without concomitant meniscal pathology) within the past 6 months to 2 years, (3) reconstructive procedure using ipsilateral autografts harvested from either the PT or soft tissue QT, and (4) ACLR performed by a fellowship-trained orthopaedic surgeon. Exclusion criteria included (1) history of lower-extremity injury or surgery, including ACL retears and revisions, within the past 6 months; (2) multiligament reconstructions; (3) inability to walk without assistance from orthotic, knee brace, or another person; (4) self-reported knee arthritis that would limit range of motion at the knee joint; and (5) pregnancy.

All grafts were chosen according to surgeon and patient preference on the basis of numerous factors, including skeletal maturity, patellar tendon length, sport or position-specific demands, cosmesis, and preexisting anterior knee pain. All QT autografts were harvested without bone plugs via a minimally invasive technique, according to Slone et al.[21] All PT autografts were harvested with bone plugs from both the patellar and tibial side. All femoral tunnels were created via an independent medial portal drilling technique. For QT autografts, graft fixation was achieved with suspensory fixation on the femoral and tibial side. For PT autografts, the femoral side was fixed with either interference screws or suspensory fixation, whereas the tibial side was fixed with interference screws. Concomitant meniscus injuries and combined procedures were noted. After ACLR, all patients received a standardized postoperative rehabilitation protocol.[22] Before testing, all participants had been cleared by the orthopaedic surgeon to return to unrestricted physical activity.

Testing Procedures

As previously described in detail,[14] participants completed testing for bilateral isometric and isokinetic knee extensor strength, knee extensor muscle activation, and functional testing including the single hop and crossover hop, as well as questionnaires providing patient reported outcomes. On a separate day from the testing described previously, a biomechanics assessment was carried out with an active marker set (PhaseSpace Motion Capture; PhaseSpace, Inc., San Leandro, CA). An experienced certified athletic trainer (J.H.) performed all testing. Markers were placed on the pelvis and lower extremities (anterior superior iliac spine, greater trochanters, medial and lateral epicondyles, medial and lateral malleoli, heels, first and fifth metatarsals, and distal second toe) with clusters on the pelvis, thighs, shanks, and feet (Fig 1). First, participants completed a familiarization session consisting of practice DVJs. The DVJ is the most frequently used lower-extremity risk assessment, with kinematic and kinetic variables having the greatest association with injury.[19] Once familiarized, participants completed a series of 3 DVJs, in which they dropped off a 20-cm box and landed on a stationary split-belt treadmill with

Fig 1. Patient setup. Marker placement and box height for performing the drop vertical jump task. The force plates are embedded into the split belt treadmill to measure individual limb kinetics.

embedded force plates (Bertec Corporation, Columbus, OH). Participants self-selected their leading leg for the drop jump and were instructed to land with each limb at the same time on each of the embedded force plates. Upon landing, participants immediately performed a maximum vertical jump. Participants were required to keep their hands on hips for the entirety of the task. Reasons for keeping hands on hips included low ceiling height in the laboratory. Research examining the role of arm motion during a drop vertical jump found no differences in VGRF during the absorption phase of landing when compared with a hands-off-hips landing strategy.[23] Trials were repeated if hands came off hips, if participants did not land with each limb on a force plate, or if participants lost control/balance. A minimum of 3 trials were collected and averaged for analyses.

Data Reduction and Analyses

Kinetic data were collected at 2,000 Hz and kinematic data were collected at 120 Hz. VGRFs and peak sagittal and frontal plane hip and knee kinematics and kinetics were collected during the deceleration phase of the initial drop landing. Moments are reported as external joint moments. A custom LabVIEW (National Instruments, Austin, TX) software program identified and extracted the peak joint angles and moments during the deceleration phase as defined from the point of initial contact (>20 N VGRF) to peak knee flexion angle during the initial drop landing.

Because of the relatively small sample size, it was determined a priori that only nonparametric statistical tests would be used for all comparisons. Mann-Whitney *U* tests were used to compare demographics, patient-reported outcomes, kinematic variables, and kinetic variables between the QT and PT autograft groups. Only the surgical limbs were used for this comparison. Wilcoxon rank-sum tests were used to compare differences between the surgical and nonsurgical limbs for both the QT and PT autograft groups. Effect sizes ($r = [Z/\sqrt{N}]$) were also calculated and interpreted as 0.1 = small, 0.3 = medium, and 0.5 = large.[24] The alpha level was set a priori at <0.05. All statistical analyses were performed using IBM SPSS Statistics 27 (IBM Corp, Armonk, NY).

Results

A total of 25 subjects met the inclusion criteria. Results are reported for 24 participants. During the data analysis process, faulty kinematic data were identified for 1 participant; therefore, this participant was removed from analysis. The QT ACLR group had 6 total combined procedures, including 5 meniscectomies and 1 meniscal repair. The PT-ACLR group had 7 total combined procedures, including 5 meniscectomies and 2 meniscal repairs. There was no statistical difference with a small effect size (Table 1). There were no statistically significant differences in demographics between the QT and PT autograft groups, but the effect size for sex approached a medium level ($r = 0.29$) because of a greater number of male patients in the QT group (Table 1). The median follow-up for all the participants is 8 months with a range of 6 to 21 months. The median (95% confidence interval) time since surgery differed by 1.5 months where the QT group was 9 months (6.8-12.1) postoperative, and the PT group was 7.5 (6.8-12.1) months postoperative. There were no statistically significant differences between groups for the patient reported outcomes but there was a medium effect size ($r = 0.30$) for KOOS Pain with a greater score for the QT group (Table 2).

There were small effect sizes and no statistically significant differences in kinetic or kinematic variables between the surgical limb of the QT and PT autograft

Table 1. Demographic Data

	QT Autograft n = 14	PT Autograft n = 10		
	Median (95% CI)	Median (95% CI)	*P* Value	Effect Size (*r*)
Sex, male/female	11/3	5/5	.26	0.29*
Age, yr	27.5 (20.3-31.2)	20.5 (18.1-24.4)	.37	0.19
Height, cm	176.6 (171.2-182.9)	171.4 (167.0-178.5)	.34	0.20
Mass, kg	82.0 (69.3-88.1)	73.3 (62.8-79.9)	.29	0.23
BMI	24.7 (22.5-27.2)	23.6 (21.6-26.2)	.51	0.14
Meniscal procedures, APM/MR	5/1	5/2	.42	0.17
Time since surgery, mo	9.0 (8.1-13.6)	7.5 (6.8-12.1)	.55	0.13
Tegner score preinjury	9.5 (7.9-9.53)	9 (8.3-9.4)	.89	0.03
Tegner score postsurgery	6 (5.8-7.6)	7 (5.7-8.1)	.71	0.07

APM, arthroscopic partial meniscectomy; BMI, body mass index; CI, confidence interval; MR, meniscal repair; PT, patellar tendon; QT, quadriceps tendon.

*Medium effect size for a between-group surgical limb comparison; all other comparisons had a small effect size.

groups (Table 3). A between-limb comparison within the QT group showed a statistically significant difference with large effect size ($r = 0.71$) for the VGRF. The knee flexion moment approached statistical significance ($P = .056$) with a large effect size ($r = 0.51$) and the knee abduction moment had a medium effect size ($r = 0.46$). The hip flexion moment had a medium effect size ($r = 0.31$), whereas the hip abduction moment approached a large effect size ($r = 0.49$). A between-limb comparison within the PT group showed a statistically significant difference with large effect size ($r = 0.80$) for the VGRF. The knee flexion moment approached statistical significance ($P = .059$) with a medium effect size ($r = 0.37$), and the knee abduction moment had a large effect size ($r = 0.53$). The hip abduction moment had a medium effect size ($r = 0.40$). For the PT group, the peak knee flexion angle also approached statistical significance ($P = .059$) with a large effect size ($r = 0.59$) and 1.1° difference in median angle. For both groups, the surgical limb had a smaller peak biomechanical variable compared with the nonsurgical limb.

Discussion

The main findings of the present study were that during a DVJ task, there were no statistically or clinically significant differences in kinetic or kinematic variables between patients who had undergone ACLR with QT versus PT autografts, and both the QT and PT autograft groups displayed kinetic deficits in the surgical limb compared to the nonsurgical limb.

Most of the research concerning ACLR functional outcomes of a DVJ pertains to the PT autograft. This study evaluated the biomechanical patterns of patients after ACLR with QT autografts, contributing evidence in support of the consistency of the QT autograft compared with the PT autograft as graft choices for ACLR. Evidence shows that the strength of the lower-extremity muscles, particularly the quadriceps, directly influences functional movement biomechanics.[25] According to Hunnicutt et al,[14] there were no significant differences in quadriceps or hamstrings strength in these patients who had undergone ACLR with QT or PT autografts. This investigation demonstrated that landing mechanics in the sagittal and frontal planes of motion

Table 2. Patient-Reported Outcomes Data

	QT Autograft n = 14	PT Autograft n = 10		
	Median (95% CI)	Median (95% CI)	*P* Value	Effect Size (r)
Lysholm	85 (92.6-90.6)	81 (77-8,89.1)	.37	0.19
IKDC	81.1 (76.4-85.9)	82.2 (68.1-85.7)	.67	0.10
KOOS pain	90.3 (85.0,93.9)	88.9 (78.1-89.2)	.15	0.30*
KOOS symptoms	82.1 (69.2-85.7)	80.4 (63.7-84.4)	.63	0.10
KOOS ADL	97.1 (89.9-97.6)	96.3 (94.0-97.6)	.84	0.24
KOOS sport	72.5 (69.3-85.4)	70.0 (59.6-77.1)	.24	0.25
KOOS QOL	65.6 (51.3-74.0)	65.6 (57.1-74.0)	.98	<0.01

CI, confidence interval, IKDC, International Knee Documentation Committee Subjective Knee Form; KOOS, Knee injury and Osteoarthritis Outcome Score; PT, patellar tendon; QT, quadriceps tendon.

*Medium effect size for a between-group surgical limb comparison; all other comparisons had a small effect size. Patient-reported outcomes data from a larger cohort of participants were previously published.[18]

Table 3. Kinetic and Kinematic Data

	QT Autograft		PT Autograft	
	Median (95% CI)		Median (95% CI)	
	Surgical	Nonsurgical	Surgical	Nonsurgical
Kinetic outcomes				
Hip flexion, Nm/kg	0.38* (0.25-0.54)	0.51 (0.36-0.67)	0.58 (0.32-0.68)	0.56 (0.06-0.67)
Hip abduction, Nm/kg	−0.40† (−0.45, −0.26)	−0.66 (−0.81, −0.33)	−0.38* (−0.49, −0.26)	−0.64 (−0.81, −0.36)
Knee flexion, Nm/kg	−0.12[b],† (−0.24, −0.11)	−0.28 (−0.42, −0.20)	−0.10* (−0.22, −0.01)	−0.27 (−0.33, −0.11)
Knee abduction, Nm/kg	−0.06* (−0.10, −0.03)	−0.12 (−0.26, −0.06)	−0.03† (−0.08, −0.01)	−0.10 (−0.22, −0.06)
VGRF, N	1.10[a],† (1.05-1.29)	1.30 (1.23-1.40)	1.10[a],† (1.00-1.27)	1.35 (1.18-1.55)
Kinematic outcomes				
Hip flexion, °	70.0 (53.8-76.4)	65.9 (53.8-75.7)	61.1 (48.5-75.9)	59.3 (58.6-76.1)
Hip abduction, °	4.6 (2.42-10.1)	3.2 (1.0-6.4)	4.3 (0.5-6.3)	3.9 (−1.3, 7.4)
Knee flexion, °	80.6 (73.0-87.6)	81.1 (74.4-91.4)	76.6[b],† (61.1-86.1)	77.6 (75.1-89.6)
Knee abduction, °	11.3 (6.8-12.5)	11.1 (8.4-19.1)	9.9 (8.2-15.2)	16.3 (9.3-17.4)

NOTE. All variables are peak values from the deceleration phase of the initial drop landing. Deceleration phase was defined as initial contact to peak knee flexion angle.

A (−) represents the opposite direction. Statistical significance: [a]$P < .05$ between surgical and nonsurgical limbs; [b]$P < .06$ between surgical and nonsurgical limbs.

CI, confidence interval; PT, patellar tendon; QT, quadriceps tendon; VGRF, vertical ground reaction force.

*Medium effect size for a within group comparison.

†Large effect size for a within group comparison. All other comparisons were nonsignificant, $P > .05$, with small effect sizes (r).

were similar when comparing the surgical limbs of the QT and PT autograft groups. This finding indicates that patients receiving the QT autograft displayed similar movement patterns to those who received the PT autograft. In previous studies of patients with PT or hamstring tendon autografts, patients were more likely to return to activity when they demonstrated better landing mechanics.[26] Although return to activity was not one of the primary outcomes of this study, the lack of differences between groups has important implications for return to activity guidelines for patients with QT autografts. A previous study of the same patients already demonstrated no differences between these groups in single-hop performance,[14] of which hop performance has also been correlated with greater rates of return to sport.[26-29] It is plausible that for patients who receive a QT autograft, clinicians can follow similar return to activity guidelines as those for patients who receive a PT autograft,[22] as more evidence supports the similarities between groups.

Although there were no biomechanical differences between the surgical limbs of QT and PT autograft groups, both groups demonstrated statistically significant decreases in VGRF of the surgical limbs. These findings are consistent with earlier reports showing decreases in VGRFs of the surgical limb.[15,30-32] Each of these studies noted a lower VGRF of the surgical limbs, regardless of graft type, when compared with the nonsurgical limbs. The decrease in VGRF on the surgical limb coupled with an increase in the nonsurgical limb is suggestive of an off-loading pattern, a compensatory or avoidance mechanism. According to Mueske et al,[15] despite the regularity of an off-loading pattern occurring in each graft type, this pattern is accentuated in patients undergoing QT or PT autograft ACLR compared with patients with hamstring autografts. For example, in our study, the median VGRF values of both ACLR PT and QT autograft surgical limbs were 1.10 Nm/kg and are consistent with previously published data for mean VGRF values in surgical limbs.[17,32] However, our data also differed from another study that presented values closer to 1.6 Nm/kg.[15] We suspect the difference between our values and those of Mueske et al.[15] is attributable to the different box heights used in each drop task, as a greater box height lends itself to greater VGRF values.[23,33] The low ceiling height in the laboratory precluded the use of a greater box height, as well as use of arms during the drop jump for participant safety purposes. ACLR patients compensate for various reasons including, quadriceps weakness,[8,32] lingering apprehension, protection of the reconstructed knee, or pain.[15] Decreased VGRF on the ACLR limb is important to consider because differences in neuromuscular and biomechanical patterns during dynamic movement tasks may be predictive of the risk of knee injury to the contralateral limb.[34] In addition, a lack of symmetry in one's movement is known as an identifiable and modifiable risk factor for ACL reinjury.[19,35]

Patients who received the PT graft had a smaller peak knee flexion angle in their surgical limb compared with the nonsurgical limb (a median difference of 1 and 1.5 degrees in the QT and PT groups, respectively) and, although not statistically significant, this result had a large effect size and is consistent with other studies examining knee flexion during landing.[15,36,37] Even though the patterns of our results are similar to previous studies, it's important to note that our peak knee flexion median is overall lower than other studies. We attribute this to the lower box height[33] used in our methods (20 cm vs 40 cm[15] and 35 cm[37]). However, other investigators[38] who examined between-leg comparisons in female patients with ACLR, found no difference between knee flexion angles during the DVJ. Landing with less knee flexion indicates the absence of moving through a wider range of motion at the joint, or a stiff landing. This landing strategy may be used to increase the perceived stability of the joint.[39] A stiff landing pattern could predispose ACLR patients to future ACL reinjury or other knee joint injuries on the basis of the premise that a decrease in knee flexion during the loading phase increases the anterior shear force at the proximal tibia.[40,41] ACLR rehabilitation programs should continue to emphasize the importance of achieving greater knee flexion angles during initial contact as part of developing a "soft" landing technique.[19,42,43]

The lower peak knee flexion moment observed in our study is like that of others and is associated with a large and medium effect for the QT and PT groups, respetively.[15,31] Of note, however, are the differences in study designs including methods, variables, and graft types.[31] For instance, some studies used 35 cm[40] and 60-cm[43] boxes for the jump landing task, as opposed to our 20-cm box. Second, a meta-analysis[31] assessed internal knee extension moments, while we measured the external moment equivalent (i.e., knee flexion moment). In addition, the meta-analysis didn't specify the type and percentage of graft types included in the analysis. A decrease in knee flexion moment after ACLR is of concern because it may represent a decrease in the ability of the quadriceps muscles to eccentrically control knee flexion torque. The diminished capacity of the quadriceps muscles to generate force hinders the ability to properly absorb shock at the knee through eccentric contractions.[39] Force not absorbed by the quadriceps means the force will be absorbed in surrounding tissues (i.e., cartilage, ligaments, tendons, etc.), resulting in the possibility of additional knee injuries. Previous data published on a similar patient population demonstrated no significant differences in isometric quadriceps strength between groups.[14] However, during the deceleration phase of the DVJ, the quadriceps are contracting eccentrically to decelerate the body[30]; therefore, future research should investigate isokinetic eccentric strength after QT autograft.

Our results showed additional clinically relevant kinetic findings when comparing between limbs within each surgical group (Table 3). Specifically, smaller joint moments for the surgical limb at the hip and knee in both the sagittal and frontal planes. External joint moments are calculated on the basis of the magnitude of external forces (VGRF) along with kinematic positioning and distance the force travels relative to the joint center.[44] Therefore, it is likely that the decrease in external joint moments observed on the surgical limb for both the PT and QT groups is driven by the smaller magnitude peak VGRF observed during the landing task.

Patient-reported outcome measures (PROMs) are valuable tools for evaluating the outcome of ACLR, particularly when used in combination with objective testing like performance-based hop tests and biomechanical analyses. Although not the primary purpose, this study reiterated[14] that within a convenience sample at varying postsurgical time points, the Knee injury and Osteoarthritis Outcome Score pain scale was the only moderate clinically significant difference between participants receiving QT and PT grafts. Because of the lack of presurgery PROMs, we are unable to determine whether these participants met the threshold for minimally clinically important difference or substantial clinical benefit for the included subjective scales. This study did not collect PROMS at a standardized time point but most of our participants were within the 6 months to 2-year window. Comparing these data with Lund et al.[11] shows our QT International Knee Documentation Committee Subjective Knee Form and Knee injury and Osteoarthritis Outcome Score PROM results were in range with their 1- and 2-year data, whereas our PT group results were either within range or exceeded their PROMs.

Our study shows that alterations in VGRF and sagittal plane knee kinematics and kinetics continue to persist in patients after ACLR. Importantly, there were no differences observed between patients who received QT versus PT autografts. Orthopaedic surgeons may elect to perform ACLR with either QT or PT autografts, and this decision should be chiefly on the basis of patient-specific determinants and the graft familiarity of the surgeon.[45] In addition, the measurements we examined are important to clinicians, as they relate to the restoration of normal lower-extremity movement patterns and decision making for returning to sport and physical activity. Currently, targeted rehabilitation guidelines and return to sport criteria widely vary. Given the current evidence, it is plausible to continue to use similar rehabilitation and return to activity guidelines for both QT and PT autograft patients.[22] However, as evidenced by the results of this study, further work is needed to address the off-loading patterns observed in individuals post-ACLR, regardless of graft type. Consistent with statements in a previous study,[35] we advocate for the use of objective, universal return-to-sport criteria to provide information to clinicians who make the decisions of when athletes return to activity. These criteria would assist in the prescription of targeted rehabilitation to detect any latent aberrant lower-extremity landing patterns. Finally, given the fact that there are no previously reported differences between isokinetic and isometric strength,[14] future research should analyze eccentric strength patterns after QT graft rehabilitation. Further studies can standardize the lead and trail limbs to establish whether peak forces are affected by self-selected, preferential lead limbs.[46]

Limitations

The interpretation of our findings should be used within the context of its limitations. Primarily, this was a study of convenience sampling with a small sample size, no participant matching, and no matched control group. Furthermore, there is a varied range of time since surgery among the participants. Despite the various times since surgery, all patients were within 6 months to 2 years postsurgery, with no significant differences in median time postsurgery of 9.0 and 7.0 months for QT and PT grafts, respectively. Likewise, because of the small sample size, we did not perform a sex-based comparison. Although there were no statistically significant differences in demographics between our QT and PT populations, including sex, we recognize the medium effect size and unbalanced distribution of males and females among groups. As a result of study design, we were not able to control for differences in rehabilitation, however, all participants received a standardized rehabilitation protocol.[22] Another limitation of the present study was that the drop height was lower in comparison with other studies examining a similar landing task. This was due to a low ceiling height in the laboratory. In addition, the lead limb in the drop jumps was self-selected by the participants.

Conclusions

Regardless of the graft-specific surgical technique, ACLR patients are returning to activity with movements that resemble an offloading pattern of the surgical limb. Coupled with the finding of an absence of differences in kinematic and kinetic variables between the QT and PT autograft groups suggests that the QT graft may be a viable alternate graft source for ACLR.

Disclosures

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References

1. Gottlob CA, Baker CL. Anterior cruciate ligament reconstruction: Socioeconomic issues and cost effectiveness. *Am J Orthop Belle Mead NJ* 2000;29:472-476.
2. Griffin LY, Albohm MJ, Arendt EA, et al. Understanding and preventing noncontact anterior cruciate ligament injuries: A review of the Hunt Valley II Meeting, January 2005. *Am J Sports Med* 2006;34:1512-1532.
3. Herzog MM, Marshall SW, Lund JL, Pate V, Mack CD, Spang JT. Trends in incidence of ACL reconstruction and concomitant procedures among commercially insured individuals in the United States, 2002-2014. *Sports Health Multidiscip Approach* 2018;10:523-531.
4. Buller LT, Best MJ, Baraga MG, Kaplan LD. Trends in anterior cruciate ligament reconstruction in the United States. *Orthop J Sports Med* 2015;3:2325967114563664.
5. Mather RC, Koenig L, Kocher MS, et al. Societal and economic impact of anterior cruciate ligament tears. *J Bone Jt Surg* 2013;95:1751-1759.
6. Gottlob CA, Baker CL, Pellissier JM, Colvin L. Cost effectiveness of anterior cruciate ligament reconstruction in young adults. *Clin Orthop* 1999;367:272-282.
7. Lohmander LS, Englund PM, Dahl LL, Roos EM. The long-term consequence of anterior cruciate ligament and meniscus injuries: Osteoarthritis. *Am J Sports Med* 2007;35:1756-1769.
8. Schmitt LC, Paterno MV, Ford KR, Myer GD, Hewett TE. Strength asymmetry and landing mechanics at return to sport after anterior cruciate ligament reconstruction. *Med Sci Sports Exerc* 2015;47:1426-1434.
9. Randsborg PH, Cepeda N, Adamec D, Rodeo SA, Ranawat A, Pearle AD. Patient-reported outcome, return to sport, and revision rates 7-9 years after anterior cruciate ligament reconstruction: Results from a cohort of 2042 patients. *Am J Sports Med* 2022;50:423-432.
10. 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? A comparative study with a mean follow-up of 3.6 years. *Am J Sports Med* 2017;45:1326-1332.
11. Lund B, Nielsen T, Faunø P, Christiansen SE, Lind M. Is quadriceps tendon a better graft choice than patellar tendon? A prospective randomized study. *Arthroscopy* 2014;30:593-598.
12. Raines BT, Naclerio E, Sherman SL. Management of anterior cruciate ligament injury: What's in and what's out? *Indian J Orthop* 2017;51:563-575.
13. Hughes JD, Burnham JM, Hirsh A, et al. Comparison of Short-term Biodex results after anatomic anterior cruciate ligament reconstruction among 3 autografts. *Orthop J Sports Med* 2019;7:2325967119847630.
14. Hunnicutt JL, Gregory CM, McLeod MM, Woolf SK, Chapin RW, Slone HS. Quadriceps recovery after anterior cruciate ligament reconstruction with quadriceps tendon versus patellar tendon autografts. *Orthop J Sports Med* 2019;7:2325967119839786.
15. Mueske NM, VandenBerg CD, Pace JL, et al. Comparison of drop jump landing biomechanics and asymmetry

among adolescents with hamstring, patellar and quadriceps tendon autografts for anterior cruciate ligament reconstruction. *Knee* 2018;25:1065-1073.
16. Lind M, Nielsen TG, Soerensen OG, Mygind-Klavsen B, Faunø P. Quadriceps tendon grafts does not cause patients to have inferior subjective outcome after anterior cruciate ligament (ACL) reconstruction than do hamstring grafts: A 2-year prospective randomised controlled trial. *Br J Sports Med* 2020;54:183-187.
17. Webster KE, Gonzalez-Adrio R, Feller JA. Dynamic joint loading following hamstring and patellar tendon anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2004;12:15-21.
18. Chang EW, Johnson S, Pollard C, Hoffman M, Norcross M. Landing biomechanics in anterior cruciate ligament reconstructed females who pass or fail a functional test battery. *Knee* 2018;25:1074-1082.
19. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med* 2010;38:1968-1978.
20. Goerger BM, Marshall SW, Beutler AI, Blackburn JT, Wilckens JH, Padua DA. Anterior cruciate ligament injury alters preinjury lower extremity biomechanics in the injured and uninjured leg: The JUMP-ACL study. *Br J Sports Med* 2015;49:188-195.
21. 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;31:541-554.
22. Hunnicutt JL, Slone HS, Xerogeanes JW. Implications for early postoperative care after quadriceps tendon autograft for anterior cruciate ligament reconstruction: A technical note. *J Athl Train* 2020;55:623-627.
23. Laffaye G, Bardy B, Taiar R. Upper-limb motion and drop jump: Effect of expertise. *J Sports Med Phys Fitness* 2006;46:238-247.
24. Fritz CO, Morris PE, Richler JJ. Effect size estimates: Current use, calculations, and interpretation. *J Exp Psychol Gen* 2012;141:2-18.
25. Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: Criteria-based progression through the return-to-sport phase. *J Orthop Sports Phys Ther* 2006;36:385-402.
26. Welling W, Benjaminse A, Lemmink K, Gokeler A. Passing return to sports tests after ACL reconstruction is associated with greater likelihood for return to sport but fail to identify second injury risk. *Knee* 2020;27:949-957.
27. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: Two-thirds of patients have not returned by 12 months after surgery. *Am J Sports Med* 2011;39:538-543.
28. Ithurburn MP, Longfellow MA, Thomas S, Paterno MV, Schmitt LC. Knee function, strength, and resumption of preinjury sports participation in young athletes following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther* 2019;49:145-153.
29. Nawasreh Z, Logerstedt D, Cummer K, Axe M, Risberg MA, Snyder-Mackler L. Functional performance 6 months after ACL reconstruction can predict return to participation in the same preinjury activity level 12 and 24 months after surgery. *Br J Sports Med* 2018;52:375-375.
30. Jeon HS, Trimble MH, Brunt D, Robinson ME. Facilitation of quadriceps activation following a concentrically controlled knee flexion movement: The influence of transition rate. *J Orthop Sports Phys Ther* 2001;31:122-132.
31. Lepley AS, Kuenze CM. Hip and knee kinematics and kinetics during landing tasks after anterior cruciate ligament reconstruction: A systematic review and meta-analysis. *J Athl Train* 2018;53:144-159.
32. Paterno MV, Ford KR, Myer GD, Heyl R, Hewett TE. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. *Clin J Sport Med* 2007;17:258-262.
33. Yeow CH, Lee PVS, Goh JCH. Regression relationships of landing height with ground reaction forces, knee flexion angles, angular velocities and joint powers during double-leg landing. *Knee* 2009;16:381-386.
34. King E, Richter C, Daniels KAJ, et al. Can biomechanical testing after anterior cruciate ligament reconstruction identify athletes at risk for subsequent ACL injury to the contralateral uninjured limb? *Am J Sports Med* 2021;49:609-619.
35. Di Stasi SL, Logerstedt D, Gardinier ES, Snyder-Mackler L. Gait patterns differ between ACL-reconstructed athletes who pass return-to-sport criteria and those who fail. *Am J Sports Med* 2013;41:1310-1318.
36. Fryer C, Ithurburn MP, McNally MP, Thomas S, Paterno MV, Schmitt LC. The relationship between frontal plane trunk control during landing and lower extremity muscle strength in young athletes after anterior cruciate ligament reconstruction. *Clin Biomech* 2019;62:58-65.
37. Gokeler A, Hof AL, Arnold MP, Dijkstra PU, Postema K, Otten E. Abnormal landing strategies after ACL reconstruction. *Scand J Med Sci Sports* 2010;20:e12-e19.
38. Ortiz A, Olson S, Libby CL, et al. Landing mechanics between noninjured women and women with anterior cruciate ligament reconstruction during 2 jump Tasks. *Am J Sports Med* 2008;36:149-157.
39. LaStayo PC, Woolf JM, Lewek MD, Snyder-Mackler L, Reich T, Lindstedt SL. Eccentric muscle contractions: Their contribution to injury, prevention, rehabilitation, and sport. *J Orthop Sports Phys Ther* 2003;33:557-571.
40. Delahunt E, Sweeney L, Chawke M, et al. Lower limb kinematic alterations during drop vertical jumps in female athletes who have undergone anterior cruciate ligament reconstruction: Lower limb kinematic alterations. *J Orthop Res* 2012;30:72-78.
41. Pandy MG, Shelburne KB. Dependence of cruciate-ligament loading on muscle forces and external load. *J Biomech* 1997;30:1015-1024.

42. Blackburn JT, Padua DA. Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clin Biomech* 2008;23:313-319.
43. Decker MJ, Torry MR, Wyland DJ, Sterett WI, Richard Steadman J. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech* 2003;18:662-669.
44. Holder J, Trinler U, Meurer A, Stief F. A systematic review of the associations between inverse dynamics and musculoskeletal modeling to investigate joint loading in a clinical environment. *Front Bioeng Biotechnol* 2020;8:603907.
45. 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;22:979-986.
46. Lim YY, Sterzing T, Teo CJY, et al. Between-limb asymmetry in kinetic and temporal characteristics during bilateral plyometric drop jumps from different heights. *J Sports Sci* 2020;38:1605-1614.