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Quadriceps Strength, Muscle Activation Failure, and Patient-Reported Function at the Time of Return to Activity in Patients Following Anterior Cruciate Ligament Reconstruction: A Cross-sectional Study

Lindsey K. Lepley, PhD, ATC[1] and **Riann M. Palmieri-Smith, PhD, ATC**[2,3]

[1]Department of Kinesiology, University of Connecticut, Storrs, CT

[2]School of Kinesiology, University of Michigan, Ann Arbor, MI

[3]Department of Orthopaedic Surgery, University of Michigan, Ann Arbor, MI

Abstract

Study Design—Cross-sectional.

Objectives—To determine if quadriceps activation failure (QAF) moderates the relationship between quadriceps strength and physical function in individuals post-anterior cruciate ligament (ACL) reconstruction.

Background—QAF may impair the recovery of physical function post ACL reconstruction, given that QAF reduces strength, and strength is related to physical function. Evidence of this relationship has been found in individuals with knee osteoarthritis, wherein patients with lower strength and greater QAF had lower levels of physical function.

Methods—Participants consisted of 52 individuals who were cleared for return to activity at an average ± SD of 7.4 ± 1.2 months post ACL reconstruction. QAF was assessed using the superimposed burst technique and quadriceps strength was assessed using concentric isokinetic contractions (Nm/kg). Physical function was quantified using a combined variable of physical (single leg hop for distance) and self-reported function (International Knee Documentation Committee form) calculated using a principal component analysis (PCPF). Simple correlations were then performed to determine the order in which variables were entered into the regression model to evaluate if QAF moderates the relationship between quadriceps strength and physical function.

Results—The combination of quadriceps strength and the interaction of strength-by-QAF predicted 30% of the variance in physical function (R^2=0.30, P<.001; PCPF = $-0.61_{strength} + 0.20_{interaction} - 1.896$); however the interaction of strength-by-QAF only accounted for 7% of the capabilities of the model (P=.023).

Corresponding Author: Riann M. Palmieri-Smith Ph.D., ATC, 4745G Central Campus Recreational Building, 401 Washtenaw Ave., Ann Arbor, MI 48109, Phone: 734-615-3154, Fax: 734-936-1925, riannp@umich.edu.

Conclusion—Physical function is largely influenced by the recovery of quadriceps strength and minimally attenuated by QAF. These data suggest that QAF may affect individuals post ACL reconstruction differently, and to a lesser extent, than knee individuals with knee osteoarthritis.

Keywords

ACL; central activation ratio; hop testing; IKDC; return to sports

INTRODUCTION

Despite the best efforts of clinicians and researchers, anterior cruciate ligament (ACL) injuries continue to occur at a high rate.[4, 24] Unfortunately, this traumatic event is not only associated with short-term consequences,[7] but also with life-long disability.[23] Namely, early onset osteoarthritis (OA)[9, 35] and decreased self-reported function,[23] are commonplace post-injury and develop despite the successful reinstitution of static knee stability achieved via ACL reconstruction. In these patients, persistent quadriceps weakness is often implicated as a primary source of disability,[20, 27] as quadriceps weakness is omnipresent,[29] and has been found to accelerate joint degeneration,[41] and result in lower quality of life.[22, 23]

Though the precise mechanism(s) of quadriceps weakness are unknown, quadriceps activation failure (QAF) is often thought to be a primary cause of strength deficits.[29, 44] QAF routinely develops following ACL injury and reconstruction[5] and occurs due to alterations in neural signaling caused by a reduction in alpha motorneuron pool recruitment and/or firing rate.[11] Importantly, the presence of QAF creates a barrier to successful strength training, as it renders an individual unable to fully volitionally contract the quadriceps muscle.[8]

Given the adverse effect of QAF on quadriceps strength,[38, 42] it seems plausible that QAF may also impair the recovery of physical function, as QAF is related to strength,[14, 17, 44] and strength is related to physical function.[6, 10, 13, 21, 31, 37] Evidence of this relationship has been found in patients with primary knee OA, wherein the magnitude of QAF has been found to moderate the relationship between quadriceps strength and physical function.[3] Specifically, Fitzgerald and colleagues[3] found that patients with OA who had low strength and greater QAF had lower function than those with similar strength but greater volitional muscle activation. This work provides evidence that QAF is a factor that should be addressed in rehabilitation programs to optimize quadriceps strength as well as physical function in those with knee OA.[3] Despite the plethora of data post ACL reconstruction that investigates the effect of QAF on strength gains,[6, 17, 40, 43] to our knowledge, an analysis that examines how QAF may affect the relationship between quadriceps strength and physical function does not exist. Understanding the relationship between QAF, strength, and physical function, is a necessary step towards the optimization of rehabilitation protocols post ACL reconstruction, as it will help to determine factors that clinicians need to target during therapy to improve physical performance and patient-reported outcomes.

The purpose of this study was to determine if QAF moderates the relationship between quadriceps strength and physical function post ACL reconstruction. We hypothesized that QAF would affect the relationship between quadriceps strength and physical function, such that higher levels of QAF would be associated with greater strength deficits, impeding the recovery of physical function.

METHODS

Participants

Participants from the current study were part of a larger clinical study designed to examine the magnitude of QAF and strength that contributes to biomechanical asymmetry post ACL reconstruction.[26] A total of 130 patients participated in the parent study which was prospectively registered in a public registry (NCT01555567). Participants were eligible for enrollment into the parent study if they met the following criteria: 1) were between 14-30 years of age, 2) were planning to undergo rehabilitation at our orthopedic clinic, 3) had an acute ACL injury (defined as reporting to a physician within 48 hours post-injury), 4) had no previous history of surgery to either knee, 5) had not sustained a previous ACL injury, and 6) did not have a known heart condition. Pregnant females were excluded.

For the current report, 52 individuals who had undergone ACL reconstruction with a bone-patellar tendon-bone autograft and had complete data for the outcome measures of interest were retrospectively selected from the parent investigation (40% of patients from parent investigation, demographic details TABLE 1). The majority of these patients (n=39, 75%) did not receive any specialized intervention as part of their care post ACL reconstruction. However, the other 13 participants were enrolled in a clinical trial that included the use of either electrical stimulation (n=6, 12%) or a combined electrical stimulation and eccentric exercise intervention (n=7, 13%) post-surgery.[18] As the overarching purpose of this manuscript was to provide a preliminary examination of the potential for QAF to moderate the relationship between strength and physical function at the time of return-to-activity following ACL reconstruction, independent of variations in rehabilitation schemes, we included all potential patients in our data set to analyze this primary relationship. Surgical reports were obtained to document any concomitant meniscal damage that required surgical intervention. The protocol for this study was approved by the University of Michigan's Institutional Review Board, and all participants provided informed consent prior to participation.

All participants completed a standard rehabilitation protocol at an orthopedic outpatient clinic. The rehabilitation protocol emphasized full knee extension range of motion immediately post-surgery and gain in knee flexion as tolerated. Progressive functional exercises and quadriceps muscles re-education and strengthening were also emphasized post-surgery. In general, the rehabilitation protocol consisted of 2 to 3 sessions per week beginning the first post-operative week, and concluded approximately 7 months post ACL reconstruction. Variations in selection of exercises existed based on individual response to treatment.

Testing scheme

Each participant completed 1 testing session during which measures of self-reported function, physical performance, quadriceps strength, and quadriceps activation were collected. Data were collected once participants had been cleared by their orthopedic surgeon to return-to-activity, which required the patient to complete a leg press test. To pass the leg press test, using the ACL reconstructed limb, participants were required to perform at least 15 repetitions against a resistance equal to 100% body weight, each repetition moving through an arc of motion from full knee extension to 90° of flexion. If a patient was unable to successfully pass the leg press test, their clearance for sport and activity participation was postponed. Additionally to be cleared for activity, orthopedic surgeons required that each patient demonstrated full range of knee motion (0-130° of flexion) and no evidence of knee joint effusion. It is important to note, that this criterion for return-to-activity is specific to our orthopedic clinic, and not necessarily supported by the current literature which include criteria such as a quadriceps strength index of 90% or greater and hop tests limb symmetry indices of 90% or greater.[36] Also, although all individuals in this study were cleared for activity/sport by our orthopedic surgeons prior to testing, not all elected to return back to competitive activity (TABLE 1), and the quadriceps index in our cohort was often found to be below the criteria recommended in the literature (TABLE 1). In fact, if our cohort would have utilized the evidence-based return to activity criteria that has emerged in the literature, only 27% (n=14) of patients would have passed the quadriceps indexes test (quadriceps strength index of 90% or greater) and 35% (n=18) of patients would have passed the hop test limb symmetry index (limb symmetry indices of 90% or greater). Further, only 15% (n=8) of our participants would have passed both tests, which further highlights the need to utilized evidence based measures when returning individuals back to activity.

Quadriceps function

To assess quadriceps strength, participants were positioned with their hips in 90° of flexion, their back supported, and their test limb securely strapped into an isokinetic dynamometer (Biodex System 3, Biodex Medical Systems, Shirley, NY, USA). Once correctly positioned, participants were asked to perform 3 maximal voluntary concentric knee extensions, moving from 90° of flexion to full knee extension, at 60°/sec. Verbal encouragement and real-time visual feedback of torque was provided to help facilitate maximal effort. This procedure was completed for both limbs, with the testing order being counterbalanced so as to minimize the potential of a learning effect. The trial with the largest peak torque for each limb was extracted and used to calculate the quadriceps index (Equation 1) to provide an indication of how well the ACL limb strength had recovered at time of return-to-activity (TABLE 1).

Equation 1. Quadriceps index

$$Quadriceps\ index = \left(\frac{ACL\ reconstructed\ limb}{contralateral\ noninjured\ limb}\right) * 100$$

The maximal knee extension torque produced across trials with the ACL reconstructed limb was normalized to body weight and used for statistical analysis.

The superimposed burst technique was utilized to quantify quadriceps activation.[3] To accomplish this, participants were required to perform maximal voluntary isometric contractions (MVICs) for knee extension, until no further improvement in torque was noted.

All participants completed a minimum of 3 MVIC trials, using the isokinetic dynamometer to provide resistance, with the knee at 90° of flexion. The peak torque collected from the MVIC trials was then entered into a custom written program (LabVIEW version 8.5, National Instruments, Austin, TX, USA) that was set to deliver a supramaximal electrical stimulus (100 pulses/sec, 600μsec pulse duration, 10 pulse titanic train, 130 volts) to the quadriceps muscle once the maximal knee extension torque had been reached and followed by a drop of 1 Newton meter.[19, 28] The electrical stimulus was delivered through 2 self-adhesive electrodes (Dura-Stick II [7×13cm] Chattanooga Group, Hixson, TN, USA) applied over the vastus lateralis proximally and the vastus medialis distally using a Grass S88 Dual Output Square Pulse Stimulator (S88, Grass Products, Natus Neurology, Warwick, RI, USA). Volitional activation of the quadriceps muscle was determined using the central activation ratio (CAR) formula (Equation 2) with the participant's peak torque generated immediately prior to the delivery of the stimulus (MVIC) being divided by the peak torque generated as a result of the electrical stimulus (MVIC + superimposed burst) and then multiplied by 100.[14] A CAR of 100 represents complete volitional quadriceps activation. The minimal QAF trial (ie, the trial with the largest CAR value which indicates the least amount of QAF) that was collected was used for statistical analysis.

Equation 2. Central activation ratio

$$Central\ activation\ ratio = \left(\frac{MVIC}{MVIC+SIB}\right) * 100$$

Physical performance

To quantify physical performance, participants performed the single leg hop test for distance. This test is a commonly used clinical tool to assess physical readiness for return-to-activity following ACL reconstruction[36] and has been shown to have high reliability.[33] To perform the test, each participant was asked to stand on their ACL reconstructed limb and hop once forward as far as possible and land on the reconstructed limb. Participants were allowed to practice the hop trial until they felt comfortable and no improvement in distance was recorded.[36] The value of the hop that covered the maximal distance (ie, longest in meters) was used for statistical analysis.

Self-reported function

To measure self-reported function, participants completed the International Knee Documentation Committee (IKDC) subjective form.[12] This self-reported questionnaire is widely used to measure knee-specific measures of symptoms, function, and sporting activity. The questionnaire consists of 18 items designed to assess the respondent's ability to perform dynamic tasks (ie, run, jump and land, start and stop quickly), activities of daily living, (ie, ascent/descent stairs, stand, kneel, rise from a chair) and symptoms (ie, stiffness, joint locking, pain, instability). Reponses types include dichotomous yes or no responses and 5-point and 11-point Likert scales. The IKDC is scored by summing the scores from the individual items and then transforming the score to a scale that ranges from 0 to 100. The transformed score is then interpreted as a measure of function, with higher scores representing greater levels of function. The transformed score was used for statistical analysis.

Statistical analysis

Prior to data analysis, a principal component analysis was performed to combine the results of the single-leg hop for distance and the IKDC score into a single principal component score of physical function (PCPF).[3] We created this PCPF variable so we could analyze our data using a more comprehensive measure of function that includes both self-reported and physical performance: 2 factors that are thought to measure different constructs of physical function.[2] To calculate the PCPF for each participant, we calculated the Z score for the single-leg hop for distance and the IKDC score variables. The Z score from these variables was then multiplied by the principal component score coefficient. The products of this calculation were then summed together to create the PCPF for each participant (Equation 3).[3]

Equation 3. PCPF calculation

$$PCPF = (component\ score\ coefficient_{hop} \times Zscore_{hop}) + (component\ score\ coefficient_{IKDC} \times Zscore_{IKDC})$$

Following the calculation of the PCPF variable, the interaction between quadriceps isokinetic strength and QAF was calculated (strength-by-QAF interaction, Equation 4).[3] This interaction variable was created so we could determine how QAF may modify (ie, affect the direction of) quadriceps strength.

Equation 4. Strength-by-QAF interaction

$$StrengthbyQAF\ interaction = (MVIC \times QAF)$$

Next, a hierarchical linear regression was performed. The order in which variables were entered into the regression model was determined by the magnitude of individual simple Pearson Product Moment correlations or Spearman Rank correlations where appropriate (TABLE 2). The total R^2, as well as the change in R^2, were calculated following the inclusion of each variable into the model (TABLE 3). The correlation coefficients were also assessed and classified as weak (0-0.4), moderate (0.4-0.7), or strong (0.7-1.0).[32]

To further examine how QAF may moderate the relationship between strength and PCPF, participants were split into a group of High QAF (CAR < 90%) and a group of Low QAF (CAR ≤ 90%, TABLE 4). Once participants were stratified into groups of High and Low QAF, 2 additional regression analyses were performed on each subgroup. Lastly, independent t-tests were performed to detect differences in demographic, QAF, strength, the interaction of strength-by-QAF, IKDC, hop distance, and PCPF between the High and Low QAF subgroups.

The α-level for all statistical tests was set *a priori* at P≤.05. Statistical analysis was performed using the Statistical Package for the Social Sciences (SPSS) software version 21.0 (IBM Corp., Armonk, NY, USA).

RESULTS

Factors related to PCPF

There was a significant, *moderately*-positive, correlation between quadriceps strength and PCPF (ρ=0.52, P<.001). Additionally, there was a significant, *moderately*-positive, correlation between the quadriceps strength-by-QAF interaction and PCPF (ρ=0.52, P<.001). Age, height, weight, concomitant meniscal injury were not associated with PCPF (P≥.05, TABLE 2). Although not statistically significant, a *weak*-positive correlation between QAF and PCPF was found (ρ=0.16, P=0.20). Thus to ensure that we accounted for any effect QAF had on PCPF, it was decided to include QAF into the final model. Hence, quadriceps strength, QAF, and the interaction of quadriceps strength-by-QAF were both entered into the model, with the interaction term entered last to determine the influence that the interaction term had on PCPF beyond that of quadriceps strength and QAF.

Relationship between QAF, strength, and PCPF

The multiple-regression model, which consisted of quadriceps strength and the interaction of strength-by-QAF, predicted 30% of the variance in PCPF (R^2=0.30, P<.001; PCPF = $-0.60_{strength} + 0.02_{interaction} - 1.896$, TABLE 3); with the strength-by-QAF interaction term accounting for only 7% of the predictive capabilities of the model (P=.023, TABLE 3). QAF was excluded by the final model, as it did not significantly contribute (ΔR^2=0.03, P=.159).

High and Low Quadriceps Activation Failure

Within the Low QAF subgroup, quadriceps strength alone accounted for 43% of the variance in PCPF (R^2=0.43 P<.001; PCPF = $0.438_{strength} - 2.427$, TABLE 3). QAF and the strength-by-QAF interaction term were excluded from the final model, as these variables did not significantly contribute (QAF: ΔR^2<0.001, P=.920; strength-by-QAF: ΔR^2=0.04, P=.149). In the High QAF subgroup, quadriceps strength, QAF and the interaction of strength-by-QAF did not significantly predict PCPF (P=.550, TABLE 3).

Participants who were in the Low QAF sub-group demonstrated significantly higher levels of CAR (t_{50}=9.241, P≤.001, TABLE 4), and a significantly higher interaction of quadriceps strength-by-QAF than the High QAF sub-group (Low QAF: 152.49±52.6; High QAF: 119.79±44.0, t_{50}=2.377, P=.029). No other significant differences were found between High and Low QAF sub-groups (P>.05).

DISCUSSION

Our results indicate that physical function at the time of return to sport following ACL reconstruction is largely influenced by the recovery of quadriceps strength and minimally attenuated by alterations in volitional muscle activation. This finding is somewhat surprising, given that we had expected that higher levels of QAF would adversely affect the recovery of quadriceps strength, which in turn, would impede physical function. However, given that our participants had relatively high levels of quadriceps activation at the time of return to activity (TABLE 1), it seems reasonable that QAF had a minimal influence on our results. The minimal impact of QAF was further highlighted when no differences in quadriceps strength, hop distance, IKDC, or PCPF was found between the High and Low QAF sub-groups (TABLE 4). Clinically, these data reinforce the concept that quadriceps strength at time of return-to-activity is largely related to physical performance tasks and patient-reported outcomes. Further, our results seem to indicate that QAF likely does not play an important role in affecting physical function at time of return-to-activity. To our knowledge this is the first investigation to examine the relationship between quadriceps strength, QAF, and physical function post ACL reconstruction.

Our findings are in contrast with previous work in patients with knee OA, wherein QAF was found to moderate the relationship between strength and physical function.[3] Accordingly, when Fitzgerald and colleagues split their cohort into groups of high and low QAF, they found that QAF continued to influence the relationship between strength and physical function.[3] Specifically, patients with higher levels of QAF demonstrated reduced physical function as compared to those with comparable levels of quadriceps weakness and little to no QAF.[3] Though it is not entirely clear as to why QAF did not play as important of a role in our study, it seems most likely that QAF had a minimal influence on function, given that most participants in our investigation had low levels of activation failure and had met clinic specific criteria to allow return-to-activity – creating a functionally homogeneous group.

Though QAF is ubiquitous in the early post-operative stages following ACL reconstruction,[29] it appears that QAF resolves overtime or has a limited effect on strength.[15] Simply put, it appears that once volitional muscle activation is recovered, the relationship between QAF and function may no longer (or may only minimally) apply. However, it is important to highlight that, although not statistically influenced by QAF, in the High QAF group 43% of the variance in physical function could be predicted, in contrast to fact that no prediction model was found for the Low QAF group (TABLE 3). As such, our data suggest that QAF likely does play some role in predicting physical function, and that greater volitional quadriceps muscle activation at return to activity seems to be related to be physical function. However, more data are needed to either confirm or refute our preliminary results. Notably, evidence collected in patients 2-15 years post ACL reconstruction indicate that alterations in muscle morphology, not volitional muscle activation, is likely the primary mechanism of chronic quadriceps weakness.[15] In contrast to individuals post ACL reconstruction, investigators have found that small changes in quadriceps activation appear to have a large effect on quadriceps muscle strength in individuals with knee OA, while muscle atrophy appears to be a secondary mechanism of weakness in these patients.[30] Given that our data were collected at return-to-activity, and our participants had fairly high levels of volitional muscle activation (mean ± SD: 91.18 ± 9.16, TABLE 1) compared to healthy individuals (CARs higher than approximately 90%[1, 25, 39]), it seems possible that alterations in muscle morphology, rather than QAF, may have been the primary mechanism of quadriceps weakness, and thus a better moderator of strength in our patient population. However, it should be noted, that controversy in the literature exists, and the mechanisms of quadriceps weakness post ACL reconstruction are not entirely clear.

Although chronic adaptations in strength appear to be driven by muscle morphology,[15] others have also found that QAF is the predominant cause of persistent weakness.[25] Due to the fact that we did not measure alterations in muscle morphology, our theory that muscle atrophy may have been a better moderator at return-to-activity should be interpreted with caution. Future investigators with magnetic resonance imaging capability should consider evaluating muscle volume to provide a more comprehensive examination of quadriceps function and detect the possible relationship between muscle atrophy, QAF, strength, and physical function. Furthermore, it would be beneficial for investigators to examine the relationship between QAF, quadriceps strength, and physical function across the recovery period, as it seems plausible that QAF may play a larger role in the early post-operative phases.[34]

Quadriceps strength was found to be the best predictor of physical function, wherein participants that demonstrated greater levels of quadriceps strength were found to demonstrate better physical function at the time of return-to-activity (TABLE 3). This result is rational, as the quadriceps muscle plays a large role in eccentrically controlling the body during movement[16] and has been found to be related to self-reported function.[6, 13, 21, 31] It was surprising, however, that quadriceps strength only predicted about 23% of PCPF (ie, physical function) at the time of return-to-activity. Although our investigation utilized a combined variable of physical function that accounted for both self-reported function and physical performance, and although it is not exactly the same, it is important to note that our statistical relationship is below previously reported data that found that quadriceps strength is highly related to hop distance post ACL reconstruction[13, 37] (range between r=0.25-0.59). In terms of our relationship between strength and self-reported function, our data are in agreement with the results of Logerstedt et al (n=55, R^2 =0.18), despite the fact that our strength data were quantified using isokinetic measures while Logerstedt and colleagues utilized isometric strength data.[21] In contrast, others have reported that quadriceps strength is more highly related to self-reported function than we have measured,[6, 31] however these studies included considerably smaller cohorts (n=15, r=0.78)[31] or individuals who had a history of 2 ACL reconstruction surgeries (n=21, r=0.63)[6] making the results between our work and the work of others difficult to compare. Importantly, recent evidence has found that simply using the magnitude of quadriceps peak torque post ACL reconstruction may not be the best predictor of function, as higher rate of torque development during isokinetic contractions and shorter time to peak torque were better associated with self-reported function.[10] Our data seem to support this concept that isokinetic torque is a better predictor of function, as when we analyzed our data set using our isometric data collected during quadriceps activation testing (TABLE 5), a reduced relationship between strength and PCPF was found, while QAF and the strength by-QAF interaction did not contribute to the model (R^2=0.20, P=0.001; $PCPF=0.837_{\text{isometric strength}}-1.953$). Given the inconsistency in regression analyses between measures of quadriceps strength, and the difficulty of comparing strength across trials,[6, 21, 31] future work should consider measuring force in different modes (isometric versus isokinetic [concentric versus eccentric]) as well as factors of force production (rate, speed, and power) to more comprehensively examine strength. Despite this, our results do indicate that the recovery of quadriceps strength is significantly related to a combined variable of physical and self-reported function. Thus, clinicians should continue to focus on utilizing interventions that are intended to increase quadriceps strength post ACL reconstruction, as quadriceps strength is an important component of patient physical test and patient-oriented outcomes.

Limitations

A limitation of this study is that alterations in muscle morphology were not assessed. Knowing if quadriceps morphology moderates or contributes to the relationship between quadriceps strength and physical function could help to provide more clinical direction of factors that can be targeted post ACL reconstruction to improve recovery. Second, though the single leg hop for distance and the IKDC are commonly used measures post ACL reconstruction to assess function, utilizing a greater number of physical (ie, triple hop for distance, crossover hop for distance, 6-meter timed hop) and self-reported measures (ie, Marx, Knee Outcome Survey-Activities of Daily Living, Visual Analog Scale, Short-Form-36) to compile our PCPF may have provided for a more comprehensive and robust principal component analysis. Similarly, our PCPF variable was modeled based on the PCPF variable that was created by Fitzgerald and colleagues, who utilized a less dynamic task (get-up and go test) to measure physical function.[3] Further, to our knowledge, no other pathological knee investigation has utilized this type of analyses/variable to examine the relationship between QAF, strength, and physical function, relationship. As such the validity of this criterion has not been objectively tested. Going forward, it would be ideal for our variable of PCPF to be tested against another variable of physical function in an ACL population that has already been validated. Third, because all of our data were collected in participants who had undergone ACL reconstruction with a bone-patellar-tendon bone autograft, these data cannot be generalized to other surgical grafts types. Lastly, due to the limited number of participants, we were unable to examine variations in rehabilitation approaches and how these differences in rehabilitation may have affected the relationship between QAF, strength, and physical function.

Clinical implications

At the time patients return-to-activity post ACL reconstruction, the results of this study indicate that physical function is, in large part, dependent on the magnitude of quadriceps force production. Alterations in quadriceps volitional muscle activity appear to minimally influence this relationship. However, it is unknown if QAF plays a more significant role in the early post-operative phases.[34] Future research will need to be conducted to determine if QAF is a moderator of quadriceps strength and function immediately following ACL reconstruction and over the course of the rehabilitation process. Furthermore, it is important to note that at return-to-activity our participants strength was below clinical recommendations of a quadriceps index of 90% or greater (TABLE 1).[36] Based on our low quadriceps indexes and the findings of this investigation, we recommend that clinicians continue to utilize interventions and therapy regimes that are capable of combating the quadriceps weakness that is common following ACL reconstruction, as strength is the primary factor that was found to influence both physical performance and self-reported function. Further, it is highly recommended that at a time when individuals are ready to return-to-activity, that clinicians utilize criteria that have been recommend by the literature[36] rather than clinic specific tests (eg, leg press test) that have not been rigorously tested.

CONCLUSION

Our results indicate that physical function at the time of return-to-activity is largely associated to the recovery of quadriceps strength and minimally attenuated by volitional muscle activation. The minimal impact of QAF on strength and physical function is most likely due to that fact that most participants had low levels of activation failure at time of return-to-activity.

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KEY POINTS

Findings

Physical function (self-reported and physical performance) was largely associated with quadriceps muscle strength and minimally attenuated by volitional muscle activation at an average of 7 months post ACL reconstruction for patients who passed specific returned to activity criteria.

Implications

After ACL reconstruction, rehabilitation should focus on utilizing interventions that address quadriceps weakness, as quadriceps strength is associated with patient oriented outcomes.

Caution

Muscle morphology was not assessed and participants in this study did not follow a standard program of rehabilitation. In addition, this study is limited to the time of return to activity and only to patients with a patellar tendon autograft.

TABLE 1

Participants demographics

Sex (n)	
	Male=32
	Female=20
Age (yrs)	20.7±5.3
Height (m)	1.74±0.11
Weight (kg)	77.3±16.4
Time post ACL reconstruction (months)	7.4±1.2
Returned to competitive sport (n)	
	Yes=35
	No=17
Concomitant meniscal surgery (n)	
	ACL-only=32
	ACL & meniscectomy=6
	ACL & meniscal repair=14
Self-reported function (IKDC)	80.9±10.9
Physical performance (single leg hop distance, m)	1.36±0.36 (range: 0.69-2.15; limb symmetry index: 84.2±15.9)
Quadriceps isokinetic strength at 60°/sec (Nm/kg)	1.55±0.56 (range: 0.64-3.11; quadriceps index: 73.6±23.5)
Quadriceps Activation Failure (superimposed burst technique, CAR)	91.18±9.16 (range: 57.31-99.95)

Abbreviations: CAR, central activation ratio; IKDC, International Knee Documentation Committee Form

Values are means and standard deviations unless otherwise indicated

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TABLE 2

Bivariate correlations between participant demographics and quadriceps function and PCPF

	PCPF
Sex	ρ=-0.15, P=.27
Age	ρ=-0.04, P=.78
Height	r=-0.12, P=.42
Weight	r=-0.34, P=.81
Concomitant meniscal surgery	ρ=-0.14, P=.42
Quadriceps isokinetic strength at 60°/sec	ρ=0.52*, P<.001
Quadriceps Activation Failure (superimposed burst technique, CAR)	ρ=0.16, P=.20
Strength–by–QAF interaction	ρ=0.52*, P<.001

Abbreviations: CAR, central activation ratio; QAF, quadriceps activation failure; PCPF, principal component score of physical function

*P<.001

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TABLE 3

Regression analysis to explain variance in PCPF

Step	Variable	R^2	ΔR^2	P
All Participants				
1	Quadriceps strength	0.23	0.23; P<.001	P<.001
2	Strength by-QAF interaction	0.30	0.07; P=.023	P<.001
Low QAF (CAR ≥ 90%)				
1	Quadriceps strength	0.43	0.43; P<.001	P<.001
High QAF (CAR < 90%)				
	No significant predictors			

Abbreviations: CAR, central activation ratio; QAF, quadriceps activation failure; PCPF, principal component score of physical function

TABLE 4

Data for participants in QAF sub-group analysis

	Low QAF (CAR ≥ 90%)	High QAF (CAR < 90%)
Total	N=34	N=18
Sex	Male=23	Male=9
	Female=11	Female=9
Age (yrs)	20.9±4.8	20.3±6.2
Height (m)	1.73±0.13	1.74±0.07
Weight (kg)	77.7±18.7	76.7±12.0
Time post ACL reconstruction (months)	7.4±1.1	7.5±1.2
Returned to competitive sport	Yes=25	Yes=10
	No=9	No=8
Concomitant meniscal surgery		
	ACL-only=22	ACL-only=10
	ACL & meniscectomy=5	ACL & meniscectomy=1
	ACL & meniscal repair=7	ACL & meniscal repair=7
Self-reported function (IKDC)	80.7±10.3	81.2±12.5
Physical performance (single leg hop distance, m)	1.41±0.37 (range: 0.69-2.15; limb symmetry index: 85.74±14.76)	1.28±0.32 (range: 0.74-1.93; limb symmetry index: 81.33±17.51)
Quadriceps isokinetic strength at 60°/sec (Nm/kg)	1.58±0.53 (range: 0.89-3.11; quadriceps index: 71.93±19.14)	1.49±0.61 (range: 0.64-3.10; quadriceps index: 76.99±30.54)
Quadriceps Activation Failure (superimposed burst technique, CAR)	96.37±2.88 (range: 90.72-99.95)*	81.39±8.96 (range: 57.31-89.63)

Abbreviations: CAR, central activation ratio; IKDC, International Knee Documentation Committee Form

Values are means and standard deviations unless otherwise indicated

*P≤.001

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TABLE 5

Isokinetic and isometric strength data

Measure	Quadriceps isokinetic strength at 60°/sec (Nm/kg)	Quadriceps isometric strength at 90° flexion (Nm/kg)
All participants	1.54±0.56 (range: 0.64-3.11; quadriceps index: 73.6±23.5)	2.38±0.72 (range: 1.19-4.39; quadriceps index: 72.77±16.78)
Low QAF (CAR ≥ 90%, n=34)	1.58±0.53 (range: 0.89-3.11; quadriceps index: 71.93±19.14)	2.58±0.74 (range: 1.22-4.39; quadriceps index: 75.01±14.05)
High QAF (CAR < 90%, n=18)	1.49±0.61 (range: 0.64-3.10; quadriceps index: 76.99±30.54)	2.00±0.53 (range: 1.19-3.00; quadriceps index: 68.54±20.80)

Abbreviations: CAR, central activation ratio

Values are means and standard deviations unless otherwise indicated.