Relationship Between Quadriceps Strength and Knee Joint Power During Jumping After ACLR

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Background: Knee joint power is significantly impaired during the propulsive phase of jumping after anterior cruciate ligament reconstruction (ACLR); however, it is currently unknown how quadriceps strength influences knee joint power.

Purpose: To (1) evaluate the relationship between quadriceps strength, joint power, and the percentage contribution of the hip, knee, and ankle joints to total limb power during the propulsive phase of jumping and (2) establish a quadriceps strength cutoff value for maximizing the likelihood of having knee joint power characteristics similar to healthy participants.

Study Design: Cross-sectional study; Level of evidence, 3.

Methods: A total of 75 participants were included in this study—40 patients who underwent ACLR 6 months before (18 females; mean age, 19.3 ± 5.7 years) and 35 healthy controls (HC) (20 females; mean age, 21.5 ± 4.5 years). Participants performed a drop vertical jump and underwent isometric quadriceps strength testing. The peak joint power was calculated as the product of the internal joint moment and joint angular velocity. Pearson product-moment correlations were used to assess the relationship between quadriceps strength and knee joint power. Paired samples *t* tests were used to quantify differences between limbs. Receiver operating characteristic (ROC) curve analysis was used to determine a quadriceps strength cutoff.

Results: The involved limbs of the ACLR cohort (INV) had significantly lower peak knee joint power and percentage contribution from the knee joint during jumping compared with the uninvolved limbs (NON) and limbs of the controls (INV, 2.5 ± 1.2 W/kg; NON, 4.4 ± 1.5 W/kg; HC, 4.3 ± 1.7 W/kg [$P < .0001$]). Quadriceps strength was associated with knee joint power in involved limbs and limbs of controls (INV, $r = 0.50$; HC, $r = 0.60$). A quadriceps strength cutoff value of 2.07 N·m/kg had an area under the ROC curve of 0.842, indicating good predictive accuracy.

Conclusion: Athletes at 6 months after ACLR demonstrated knee-avoidant jumping mechanics and had significant reductions in knee joint power on the involved limb. A quadriceps strength cutoff value of 2.07 N·m/kg can help predict which athletes will display knee joint power characteristics similar to those of healthy controls.

Keywords: anterior cruciate ligament; biomechanics; quadriceps; return to sport

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Anterior cruciate ligament (ACL) tears are one of the most common athletic knee injuries for those participating in cutting and pivoting sports, with more than 200,000 tears occurring annually.[6,7,29] To maximize knee stability and function, athletes typically elect to undergo ACL reconstruction (ACLR) with an expectation to return to competitive athletics within 6 to 9 months.[13] Although most athletes will return to some level of sports participation, approximately half will not be able to return to their previous level of performance within 2 years after surgery.[3,4] While the reasons for not returning to preinjury levels of play are multifactorial in nature (ie, psychological, physical, and psychosocial), failure to restore quadriceps strength in the surgical limb has been well-established in the literature as one of the most significant predictors of poor functional outcomes.[2,11,14,25,37,47]

Only 1 in 5 athletes is meeting the current recommendations for quadriceps strength symmetry (≥90%) at the time of return to sport (RTS), which is likely contributing to the low return to performance rates.[8,10,13] Despite quadriceps strength testing being an isolated assessment of knee joint function, it is strongly associated with the performance of dynamic multijoint tasks like vertical jumping.[1,15,42] At the time of RTS, athletes with deficits in quadriceps strength demonstrate significantly lower single-limb and double-limb vertical jump heights compared with their uninvolved limb and healthy controls, respectively.[17,24] While these findings are intriguing, the majority of the literature investigating the

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The Orthopaedic Journal of Sports Medicine, 11(3), 23259671231150938
DOI: 10.1177/23259671231150938

relationship between quadriceps strength and jump performance after ACLR has focused on the analysis of vertical ground reaction forces, which are unable to provide joint-specific kinetics and kinematics.[17,36] While the use of vertical ground-reaction forces to analyze jump performance can provide valuable information regarding interlimb differences in power output and jump height, it is unable to provide insight into potential intralimb compensations or the relative performance contributions from the hip, knee, and ankle joints. Therefore, analysis of individual joint powers and their percentage contribution to jump performance may be better indicators of RTS readiness than total power output alone.[33]

To date, few studies have analyzed lower extremity joint power contributions to vertical jumping in patients after ACLR, and most studies have focused exclusively on joint power absorption during the landing phase of the jump.[19,27,35,45] While the landing phase may be relevant in regard to the second injury risk, analysis of the propulsive phase of jumping may elucidate return to performance readiness.[26] Two recent studies analyzed joint work and power generation during the propulsive phase of jumping and found evidence to suggest that knee joint power is significantly reduced in the involved limb at 6 to 9 months after ACLR.[23,34] Interestingly, both studies found a redistribution of effort to the hip joint as a potential compensatory jumping strategy in response to the loss of knee joint power after ACLR.[23,34] While 1 study found moderately positive associations between quadriceps strength and percentage power contribution from the knee joint, the other study only tested athletes who had already met the recommended 90% quadriceps strength symmetry goal and did not provide a comparative analysis.[23,34] These studies provide intriguing preliminary evidence that knee joint power is impaired after ACLR; however, both studies tested only male athletes in their 20s, limiting generalizability to other athletic populations. Additionally, both studies analyzed only single-leg iterations of the vertical jump with no analysis of a potentially more sport-specific double-limb jumping task. It remains unclear how postoperative deficits in quadriceps strength affect intralimb joint power distribution of the lower extremity during a double-limb jumping task. In addition, it is unknown whether there is a requisite amount of quadriceps strength needed for the resolution of the compensatory movement strategies and knee-avoidant mechanics frequently observed during jumping after ACLR.

The primary purpose of this study was to evaluate the relationship between maximal isometric quadriceps strength, peak joint power generation, and the relative percentage contribution of the hip, knee, and ankle joints during the propulsive phase of a drop vertical jump (DVJ). Secondarily, we aimed to establish a normative isometric quadriceps strength cutoff for maximizing the likelihood of patients post–ACLR having knee joint power characteristics similar to those of healthy controls during jumping. We hypothesized that the involved limb of patients with ACLR would have significantly lower peak knee joint power and percentage power contributions from the knee joint compared with the uninvolved limb. Additionally, we hypothesized that peak knee joint power and percentage contribution would be associated with quadriceps strength in both patients with ACLR and healthy controls.

METHODS

Study Design and Participants

This cross-sectional study was a secondary analysis of previously collected data from a research protocol that was approved by the institutional review board of the University of Kentucky. All participants provided informed consent for participation. This study aimed to compare patients who underwent ACLR 6 months earlier with healthy controls. Participants from both cohorts were recruited between 2018 and 2021, and all testing took place in the University of Kentucky BioMotion Laboratory. Patients with ACLR were recruited from physical therapy clinics in the surrounding area, and healthy controls were recruited through advertisements within the local community. All testing of the patients with ACLR for this study was conducted at the 6-month postoperative time point.

Patients with ACLR were eligible for study enrollment if they were skeletally mature and self-reported as level 1 or 2 athletes before their injury. Patients were excluded if they had a history of previous ACL injury on either limb, sustained a complete knee dislocation, were older than 35 years, or had a body mass index of >35. All ACL tears were confirmed by clinical evaluation and diagnostic testing, and all ACLRs were performed by surgeons from the same orthopaedic practice. Control participants were eligible for enrollment if they were between the ages of 15 and 35 years, self-reported as level 1 or 2 athletes at the time of assessment, had no history of lower extremity injury in the previous 6 months, and had no history of surgeries or health conditions that may have affected their physical performance. Level 1 athletes are defined as being involved in competitive or recreational sports involving jumping, pivoting, and cutting (ie, gymnastics, basketball, and soccer).[12] Level 2 athletes are defined as being involved in competitive or recreational sports that involve less jumping and

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Final revision submitted October 18, 2022; accepted November 2, 2022.

One or more of the authors has declared the following potential conflict of interest or source of funding: Research reported in this publication was supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health (award No. 5R01AR072061 to B.N.). D.J. has received consulting fees; nonconsulting fees; royalties from Smith & Nephew; and hospitality payments from Linvatec and Xiros. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval for this study was obtained from the University of Kentucky (ref No. 47953).

cutting than level 1 (ie, baseball, tennis).[12] For this study, we also regarded competitive endurance athletes (ie, track, cross-country, and cycling) as being level 2.

Isometric Quadriceps Strength Testing

The isometric quadriceps strength was assessed bilaterally with a Biodex Multi-Joint System 4 Isokinetic Dynamometer (Biodex Medical Systems, Inc). Each participant was seated with hips flexed to 90°, knees flexed to 90°, and the dynamometer secured to the shank approximately 5 cm proximal to the medial malleolus. Straps were placed across the chest, torso, and thigh to limit extraneous motion. The uninvolved limb was tested before the involved limb for the ACLR cohort. The torque signal was sampled at 100 Hz and processed using a custom MATLAB code (MathWorks Inc). The torque signal was filtered using a fourth-order, low-pass Butterworth zero-lag digital filter with a 24-Hz cutoff frequency.

The peak quadriceps torque was recorded during 5-second maximal voluntary isometric contractions. One submaximal practice trial was completed to allow for familiarization with the task, followed by 4 test trials. Participants were instructed to kick and hold as hard and fast as they could for each trial. Maximum verbal encouragement was provided. Participants were given 30 seconds of rest between trials and 5 minutes of rest between limbs. For each limb, the peak quadriceps torque was averaged from the 4 test trials and normalized to body mass.

Three-Dimensional Motion Analysis

Using a previously reported marker set, 52 retroreflective markers were placed on each participant.[22,32] Of these markers, 27 were placed on anatomical landmarks—including the sternal notch, spinous process of C7, bilateral superior acromion processes, posterior L5/S1 vertebral joint, bilateral greater trochanters, bilateral iliac crests, bilateral medial and lateral femoral condyles, bilateral medial and lateral tibial condyles, bilateral medial and lateral malleoli, bilateral first and fifth metatarsal heads, and bilateral distal foot. Also, 25 of these markers were used for tracking—including 4 rigid plates secured to bilateral distal thighs and shanks with 4 markers on each plate; 3 markers identifying the proximal, distal, and lateral heel on the rearfoot of each shoe; and 3 markers identifying the anterior right thigh, shank, and foot to differentiate the right limb from the left limb.

DVJ Testing

Each athlete performed the DVJ test after preparation for 3-dimensional motion analysis. Three trials were collected with a 12-camera motion capture system (Motion Analysis Corp) at a sampling rate of 200 Hz. Dual force plate data were recorded at a sampling rate of 2000 Hz from an instrumented Bertec treadmill (Bertec). The participant started the DVJ test on a 30-cm box and was instructed to drop off the box, land both feet simultaneously on the force plates, and then immediately execute a maximal effort vertical jump (Figure 1). The mean of the 3 trials was used for subsequent data analysis.

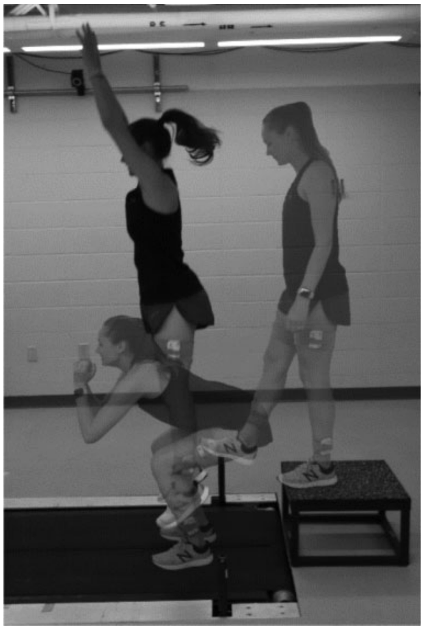

Figure 1. A drop vertical jump from a 30-cm box onto dual force plates. The propulsive phase was defined as the period from the peak knee flexion angle to toe-off.

Data Processing

Visual 3-dimensional software (C-Motion) and custom LabView code (National Instruments) were used to filter the data and perform inverse dynamics to determine internal moments for the hip, knee, and ankle joints. Marker trajectories and force data were filtered at 10 Hz using a fourth-order, low-pass, zero-lag Butterworth filter. The joint angles and moments were calculated using Cardan *X-Y-Z* angles rotation with distal segments referenced to the proximal model.[32] All data were extracted from the propulsive phase of jumping, which was defined as the duration of the stance between the peak knee flexion angle to toe-off. Toe-off was defined as the point at which the vertical ground reaction force was <20 N. The peak joint power was calculated as the product of joint angular velocity and internal joint moment.[43] The percentage contribution from the hip, knee, and ankle joints was calculated by dividing the individual joint powers by the summed joint power from the respective limb.[43] The peak joint power was then normalized to body mass.

Statistical Analysis

Statistical analysis was performed with SPSS Version 27.0 (IBM Corp), with statistical significance defined as $P < .05$ for all analyses. Descriptive statistics (means and standard deviations) were calculated for both groups for all demographic variables. Differences between the ACLR and control groups in baseline characteristics were assessed with

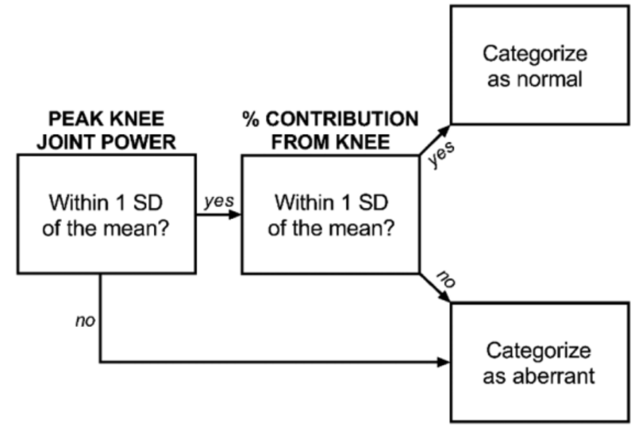

Figure 2. A decision tree for dichotomous categorization of limbs for receiver operating characteristic curve analysis.

independent-sample t tests (age, sex, height, weight, and body mass index). Differences between limbs for all variables were assessed with paired samples t tests for both study cohorts. Differences between uninvolved limbs of the ACLR group and healthy control limbs were assessed using independent-sample t tests. Preliminary between-limb statistical testing indicated no significant difference between the right and left limbs of the control cohort. Additionally, when categorizing by self-reported limb dominance, there was no statistical difference between dominant and nondominant limbs. Therefore, limb dominance was not taken into consideration as part of the final analyses. The Pearson product-moment correlation coefficient was calculated to measure the strength of the relationship between isometric quadriceps strength and peak knee joint power in the ACLR and control groups. No a priori sample size calculation was performed for this secondary analysis.

ROC Curve Analysis

As part of the secondary analyses, a receiver operating characteristic (ROC) curve was constructed to determine the capacity of continuous normalized quadriceps peak torque to predict knee joint power characteristics during jumping. The area under the ROC curve (AUC) was used to determine if normalized quadriceps peak torque could accurately identify which limbs displayed knee joint power characteristics similar to those of healthy controls while jumping. The strength of the AUC was interpreted as having excellent diagnostic accuracy (≥ 0.9), good accuracy (≥ 0.8 to <0.9), moderate accuracy (≥ 0.7 to <0.8), poor accuracy (≥ 0.6 to <0.7), or nonmeaningful[31](≤ 0.6). The optimal sensitivity and specificity were then determined by selecting the value located closest to the upper left-hand corner of the ROC curve.

We defined "normal" knee joint power characteristics as having peak knee joint power and a knee joint power contribution percentage of ≤ 1 SD from the mean of the control group, while we defined "aberrant" knee joint power characteristics as being >1 SD below the mean (Figure 2). Both peak joint power and percentage contribution were chosen as reference criteria to increase the stringency of categorization for normal knee joint power characteristics and to capture a more comprehensive picture of knee joint function. Reference values for normal knee joint power characteristics were calculated by pooling healthy limbs from the control participants and subtracting the standard deviation from the mean. For the control group, a randomization scheme was used to choose either the right or left limb from each participant to be included in the final analysis. For the ACLR group, the surgical limb was chosen for inclusion in the analysis. The limbs were then categorized into dichotomous groups based on whether or not they met both conditions of normality (Figure 2). Participants who met both conditions were considered to have the positive condition and those who did not were considered to have the negative condition.

TABLE 1
Participant Demographics (N = 75)[a]

	ACLR Group (n = 40)	Control Group (n = 35)	P
Age, y	19.3 ± 5.7	21.5 ± 4.5	.08
Sex, n	18 F, 22 M	20 F, 15 M	.30
BM, kg	69.8 ± 13.4	66.9 ± 13.6	.96
Height, m	1.70 ± 0.10	1.70 ± 0.11	.34
BMI	24.1 ± 3	21.5 ± 4.5	.09
Graft type, n	38 BPTB, 2 HS	—	—
Meniscal pathology, n	29	—	—
Level 1 athletes, n	32	27	—

[a] Data are reported as mean ± SD unless otherwise indicated. Dashes indicate areas not applicable. ACLR, anterior cruciate ligament reconstruction; BM, body mass; BMI, body mass index; BPTB, bone–patellar tendon–bone; F, female; HS, hamstring; M, male.

RESULTS

A total of 40 athletes (22 men; 18 women; mean age, 19.3 ± 5.7 years), who underwent primary ACLR 6 months earlier, and 35 healthy controls (15 men; 20 women; mean age, 21.5 ± 4.5 years) underwent strength and performance testing according to the approved protocol. Post hoc power analysis with an alpha level of .05 demonstrated 99.8% power for the present study to detect differences between groups in knee joint power. Table 1 shows the characteristics of the 2 cohorts. For the 40 patients with ACLR, the reconstruction technique included 2 hamstring autografts and 38 bone–patellar tendon–bone autografts, and 29 patients had concomitant meniscal injury requiring additional surgical intervention.

Isometric Quadriceps Strength

The ACLR group had significantly lower quadriceps peak torque ($P < .001$) on their involved limb (1.85 ± 0.53 N·m/kg) compared with their uninvolved limb (2.95 ± 0.54 N·m/kg). The control group had no significant differences (P = .16)

TABLE 2
Control Left Limb Comparative Strength and Biomechanical Data[a]

	ACLR: Involved (n = 40)	ACLR: Uninvolved (n = 40)	*P*	Control Limb (n = 35)	*P*[b]
Quadriceps peak torque, N·m/kg	1.85 ± 0.53	2.95 ± 0.54	**<.001**	2.49 ± 0.75	**.001**
Joint power, W/kg					
Hip	3.9 ± 1.1	3.9 ± 1.2	.68	4.3 ± 1.3	.23
Knee	2.5 ± 1.2	4.4 ± 1.5	**<.001**	4.3 ± 1.7	.07
Ankle	4.8 ± 1.2	5.9 ± 1.5	**<.001**	5.6 ± 1.3	.46
Total	11.2 ± 2.4	14.2 ± 2.9	**<.001**	14.2 ± 2.8	.49
Joint Power, %					
Hip	35.7 ± 8.2	27.5 ± 6.3	**<.001**	30.3 ± 6.9	**.02**
Knee	21.6 ± 8.5	31.0 ± 7.5	**<.001**	30.1 ± 8.9	.15
Ankle	42.7 ± 6.5	41.6 ± 7.3	.22	39.6 ± 6.8	.50

[a] Data are reported as mean ± SD unless otherwise indicated. Bold *P* values indicate statistically significant differences between the compared groups ($P < .05$). ACLR, anterior cruciate ligament reconstruction..

[b] Uninvolved limb versus healthy left limb.

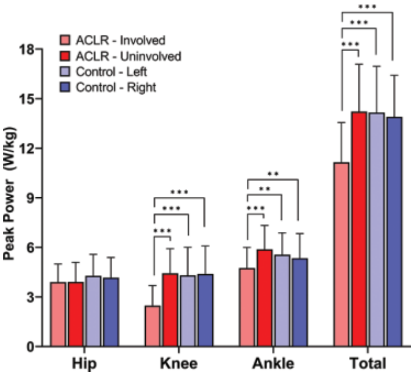

Figure 3. Lower extremity joint power comparisons across groups. The involved limb of the ACLR group had significant reductions in knee joint power, ankle joint power, and total limb power compared with the uninvolved limb and both limbs of the control group. Statistically significant difference: $^{**}P < .01$; $^{***}P < .001$. ACLR, anterior cruciate ligament reconstruction.

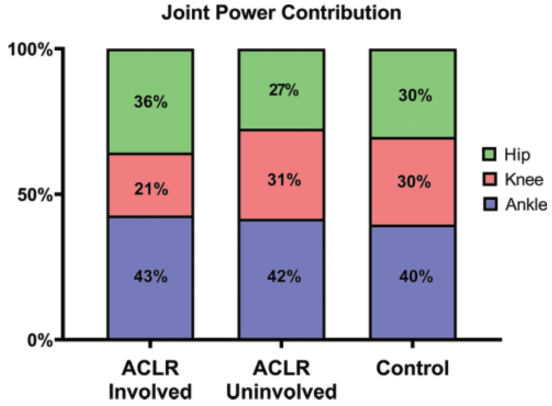

Figure 4. The joint power contribution of the lower extremity compared across groups. The involved limb of the ACLR group displayed significantly lower contributions from the knee joint and significantly larger contributions from the hip joint compared with the uninvolved limb and the healthy control limb. ACLR, anterior cruciate ligament reconstruction.

between the left (2.49 ± 0.75 N·m/kg) and right limbs (2.55 ± 0.77 N·m/kg). The uninvolved limbs of the ACLR cohort were significantly stronger than those of the controls ($P = .001$) (Table 2).

Pearson product-moment correlations revealed a strong to moderate relationship between isometric quadriceps peak torque and knee joint power in the involved limb of the ACLR group ($r = 0.50$; $P = .001$) and in both limbs of the control group (right: $r = 0.61$, left: $r = 0.59$; $P < .0001$). The uninvolved limb of the ACLR group had a weak positive correlation to its relative isometric quadriceps strength ($r = 0.21$; $P = .19$).

Peak Power and Percentage Joint Power Contribution

The involved limb of the ACLR group had significantly lower ($P < .001$) peak knee joint power (2.5 ± 1.2 W/kg), peak ankle joint power (4.8 ± 1.2 W/kg), and total limb power (11.2 ± 2.4 W/kg) compared with their uninvolved limb and both limbs of controls (Table 2) (Figure 3). There were no significant differences in peak hip joint power across all groups. With regard to percentage contribution, ACL-reconstructed limbs had significantly lower ($P < .001$) contributions from the knee (21.6% ± 8.5%) compared across groups and a relatively higher contribution from the hip joint (35.7% ± 8.2%) (Figure 4). Additionally, the uninvolved limb of the ACLR group had a lower percentage contribution from the hip (27.5% ± 6.3%) compared with that of the healthy controls (30.3% ± 6.9%). There were no significant differences across groups for percentage contribution from the ankle (Table 2).

ROC Curve Analysis

Normalized isometric quadriceps peak torque displayed good predictive accuracy with an AUC of 0.842 (95% CI, 0.749-0.935) for identifying limbs with knee joint power characteristics similar to those of healthy controls during the propulsive phase of a DVJ test. A strength value of 2.07 N·m/kg was the optimal cutoff threshold, with a prediction sensitivity of 0.71 and specificity of 0.85 (Figure 5).

We found that 67.5% of the ACLR group (n = 27) did not meet the minimal threshold of 2.07 N·m/kg for quadriceps strength on the involved limb, and 63% (n = 25) demonstrated aberrant knee joint power characteristics while jumping (Table 3).

DISCUSSION

Consistent with the stated hypothesis, ACL-reconstructed limbs had significantly lower peak knee joint power and percentage contribution from the knee compared with both the uninvolved limbs and the limbs of the healthy controls (see Figures 3 and 4). Secondarily, an isometric quadriceps strength cutoff of 2.07 N·m/kg was established as having good (AUC = 0.842) accuracy in identifying which limbs demonstrated knee joint power characteristics similar to the healthy control group during the DVJ test (see Figure 5).

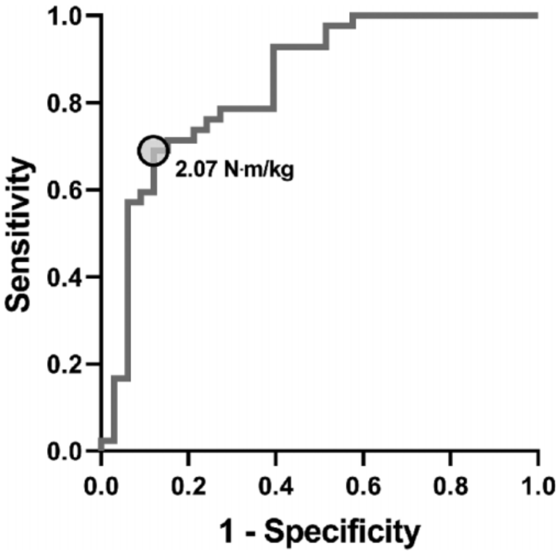

Figure 5. The ROC curve for normalized isometric quadriceps strength predicting knee joint power characteristics similar to those of healthy controls. A strength cutoff value of 2.07 N·m/kg optimized the specificity (0.85) and sensitivity (0.71) of prediction. The AUC of 0.842 demonstrated good predictive capacity. AUC, area under the curve; ROC, receiver operating characteristic.

Consistent with previous work investigating knee joint power production during jumping after ACLR, we found significant reductions in knee joint power in ACL-reconstructed limbs.[23] In regard to joint power distribution, we found that ACL-reconstructed limbs had a significantly lower percentage contribution from the knee joint and a higher percentage contribution from the hip joint compared with both their uninvolved limb and limbs of healthy controls. Interestingly, the mean peak hip joint power of ACL-reconstructed limbs was not significantly different from that of the uninvolved limbs or limbs of healthy controls (Figure 3). These findings indicate that the increased percentage contribution of the hip observed in ACL-reconstructed limbs may not be due to a redistribution of efforts to the hip as suggested by previous work.[16] Rather, the hip joint of the ACL-reconstructed limb is contributing a larger relative percentage to total limb power because of the significant losses of power observed at the knee and the ankle. Although these findings are novel, they are only generalizable to double-limb iterations of vertical jumping and cannot be extrapolated to single-leg jumping tasks.

The significant reductions in peak knee joint power observed among ACL-reconstructed limbs were related to deficits in quadriceps strength. We found a significant positive relationship between isometric quadriceps strength and knee joint power generation during the DVJ test in the ACL-reconstructed limbs ($r = 0.50$; $P = .001$). A similar relationship between knee joint power and quadriceps strength was found in both limbs of the healthy control group ($r = 0.61$ [right] and $r = 0.59$ [left]; $P < .0001$), which is consistent with previous literature.[28,36] Interestingly, no significant correlation between knee joint power and quadriceps strength was found on the uninvolved limb of the ACLR cohort ($r = 0.21$; $P = .19$). Considering that the uninvolved limb had strength levels greater than those of healthy controls, the weaker involved limb may have limited the ability of the uninvolved limb to perform optimally during a bilateral task. Previous work has shown that the

TABLE 3
Contingency Table for Quadriceps Strength Cutoff of 2.07 N·m/kg[a]

	Knee Joint Power[b]		
Quadriceps Strength	Normal	Aberrant	Total
<2.07 N·m/kg	12 (5 ACLR, 7 control)	27 (22 ACLR, 5 control)	39 (27 ACLR, 12 control)
≥2.07 N·m/kg	30 (10 ACLR, 20 control)	6 (3 ACLR, 3 control)	36 (13 ACLR, 23 control)
Total	42 (15 ACLR, 27 control)	33 (25 ACLR, 8 control)	75 (40 ACLR, 35 control)

[a] Data are reported as No. of participants. Normal and aberrant refer to knee joint mechanics during the DVJ. ACLR, anterior cruciate ligament reconstruction; DVJ, drop vertical jump.

[b] A knee joint power of >1 SD from the control group mean was defined as normal, and a knee joint power of >1 SD below the control group mean was defined as aberrant.

uninvolved limb undergoes alterations in jumping kinematics after ACLR; however, it is unknown what factors are driving these biomechanical changes in performance.[18]

Our findings regarding joint power alterations during the propulsive phase of jumping offer intriguing insights into jump performance after ACLR. Nevertheless, motion capture and sophisticated biomechanical movement analysis are not readily accessible to most clinicians and patients. Establishing quadriceps strength cutoff values that can help predict knee biomechanics during dynamic athletic tasks can be useful for making more objective decisions regarding high-level rehabilitation progressions. There is no consensus on when a patient is ready to start performing high-level sports activities such as jumping and sprinting, and most clinicians rely solely on measures of the limb symmetry index to determine readiness.[13,20,38] Utilization of the uninvolved limb as a reference may not provide an accurate representation of the previous function and does not consider the requisite strength capacity that may be needed to perform certain sport-specific tasks.[30,46] We determined through the ROC curve analysis that a quadriceps peak torque cutoff value of 2.07 N·m/kg provided good (0.842) accuracy in predicting whether or not an athlete would demonstrate knee joint power characteristics similar to those of healthy controls. The cutoff quadriceps strength value of 2.07 N·m/kg provides a realistic clinical target and could assist clinicians in making clinical decisions regarding an athlete's performance capabilities and readiness for RTS.

Despite the large body of literature supporting the importance of regular quadriceps strength testing after ACLR, almost half of clinicians continue to use time from surgery as the sole criterion to assess readiness to RTS after ACLR.[8] Although 6 to 9 months after surgery is a commonly recommended time frame for returning to competitive athletics, the majority of athletes may not yet be physically prepared to perform at a high level.[5,8,20] We found that 67.5% of the ACLR cohort did not meet the minimal threshold of 2.07 N·m/kg for quadriceps strength on the involved limb, and 63% ($n = 25$) demonstrated aberrant knee joint power characteristics while jumping (see Table 3). While the deficits in quadriceps strength on the involved limb would likely be deleterious to athletic performance, they may also lead to chronic underloading of the tibiofemoral and patellofemoral joints.[21,26,35] Chronic underloading of the knee joint after ACLR has been shown to lead to posttraumatic osteoarthritis and other long-term joint health issues, making restoration of quadriceps strength imperative.[9,44]

Limitations

This work is not without limitations. For example, the ACLR group was tested 6 months postoperatively, which is the earliest suggested time point for RTS. It is unknown whether these aberrant movement mechanics resolve over time, which may help to elucidate the appropriate length of time needed for a successful RTS. Additionally, the majority of the ACLR group in this study had bone-patellar tendon-bone grafts and concomitant meniscal pathology. It has been established that patients with bone-patellar tendon-bone grafts may take longer to regain quadriceps strength than patients with other ACL graft types (ie, hamstring autograft, allograft, etc) and may experience more frequent anterior knee pain—all of which may have contributed to the jumping mechanics observed in this study.[40,41]

With regard to the statistical analysis, the normative values used to dichotomize groups for the ROC curve were based on the investigated healthy cohort from this study and may not be representative of a population outside of this particular demographic. Additionally, the healthy controls had significantly lower quadriceps strength than the uninvolved limb of the ACLR group. This discrepancy in strength may be secondary to the higher distribution of level 1 athletes in the ACLR group or as a result of the rehabilitation process itself. We also note that the normative quadriceps strength value of 2.07 N·m/kg is derived from maximal isometric testing at 90° of knee flexion and cannot be extrapolated to isokinetic testing or isometric testing performed at other knee angles. We acknowledge that most clinicians do not have access to an isokinetic dynamometer; however, the increasing availability of cost-effective low-tech (ie, load cell, push-pull dynamometer) equipment that has been validated for isometric strength testing makes these findings more accessible.[39] Lastly, it should be noted that the suggested strength cutoff of 2.07 N·m/kg has not been shown to reduce reinjury risk and can only be applied to the context of the present study.

CONCLUSION

This study has provided preliminary evidence suggesting that quadriceps weakness of the involved limb 6 months after ACLR leads to a loss of knee joint power generation and knee-avoidant mechanics during a DVJ test. The findings of this study suggest that there is a requisite amount of quadriceps strength ($\geq$2.07 N·m/kg) needed for the knee joint to contribute normally to a vertical jumping task. Although this study did not investigate sex-based differences, recent work has provided evidence that the suggested cutoff of 2.07 N·m/kg is a reasonable strength target for both men and women in the later phases (6-9 months) of ACL rehabilitation.[40] Considering that strength is a trainable physical quality, clinicians should focus on restoring quadriceps strength in patients after ACLR and test strength at regular intervals throughout the rehabilitation process. Gaining a deeper understanding of how quadriceps strength affects lower extremity joint power generation after ACLR may help clinicians select rehabilitation interventions specifically targeted at improving athletic capabilities and returning to performance rates.

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