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Associations Among Quadriceps Strength and Rate of Torque Development 6 Weeks Post Anterior Cruciate Ligament Reconstruction and Future Hop and Vertical Jump Performance: A Prospective Cohort Study

Persons who have undergone anterior cruciate ligament (ACL) reconstruction are at increased risk of premature knee osteoarthritis,[6] an association that may be the result of abnormal knee loading.[5] During a vertical jump, kinetic measures such as

STUDY DESIGN: Prospective cohort.

BACKGROUND: Quadriceps strength is associated with hop distance and jump height in persons who have undergone anterior cruciate ligament (ACL) reconstruction. However, it is unknown whether the ability to rapidly generate quadriceps torque in the early phase of recovery is associated with future hopping and jumping performance in this population.

OBJECTIVE: To evaluate the prospective associations among quadriceps strength and rate of torque development (RTD) and single-leg hop for distance, vertical jump height, vertical ground reaction force (vGRF), and vertical force loading rate during a landing task in persons who have undergone ACL reconstruction.

METHODS: Seventy patients with unilateral ACL reconstruction participated. At 6 weeks post ACL reconstruction, isometric quadriceps strength and RTD were measured using a dynamometer. At 6 months following ACL reconstruction, patients performed the single-leg hop for distance test. Patients also performed the single-leg vertical jump test on a force plate that measured maximum jump height, vGRF, and average loading rate during landing.

RESULTS: Both quadriceps strength and RTD at 6 weeks post ACL reconstruction were associated with all hopping and jumping measures at 6 months post ACL reconstruction ($P \leq .04$). Single-leg hop distance was associated more closely with quadriceps strength than with quadriceps RTD ($P = .05$), and vertical jump height and vGRF measures were associated more closely with quadriceps RTD than with quadriceps strength ($P = .05$ and $P < .01$, respectively). Both quadriceps measures were associated with loading rate.

CONCLUSION: Quadriceps strength and RTD are complementary but distinct predictors of future hopping and jumping performance in persons who have undergone ACL reconstruction. These findings may contribute to improved rehabilitation of patients who are at risk for poor jumping/hopping performance and abnormal knee loading. *J Orthop Sports Phys Ther 2017;47(11):845-852. Epub 13 Oct 2017. doi:10.2519/jospt.2017.7133*

KEY WORDS: *ACL, explosive strength, knee, loading, landing, limb symmetry, postoperative strength, stability*

the vertical ground reaction force (vGRF) or loading rate may better reflect the ability of the lower extremity to dissipate or control landing forces than do standard clinical measures of jump height.[5] Previous studies have reported between-limb asymmetries in vGRF and loading-rate measures among athletes who were cleared to return to sports following ACL reconstruction[21] and in patients 2 years post ACL reconstruction.[23] Thus, identifying the modifiable predictors of these kinetic measures could present opportunities to provide effective rehabilitation for patients who are at risk for abnormal knee loading.

Limited and mixed evidence has suggested that in patients who have undergone ACL reconstruction, quadriceps strength may be associated with kinetic measures of vGRF and loading rate during landing from a drop jump.[14,26] Quadriceps strength, however, represents just one aspect of muscle performance. Another measure of muscle performance is the rate of torque development (RTD). Previous research has shown that both quadriceps strength and RTD are impaired in patients who have

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undergone ACL reconstruction.[13,16,17] The ability of the quadriceps to generate torque rapidly is important in achieving dynamic knee stability during high-impact activities such as hopping and jumping. During a vertical jump, quadriceps RTD could potentially provide additional benefit over quadriceps strength, as the impact-absorption phase occurs over a short period (approximately 150 milliseconds).[22] As such, the knee musculature has limited time to control and attenuate the forces acting on the knee.

Previous studies of healthy persons have shown quadriceps RTD to be important when considering jump height performance.[4,8,9] In individuals who have had ACL reconstruction, higher levels of quadriceps RTD, as opposed to quadriceps strength, have been shown to be associated with better self-reported knee function.[13] While the aforementioned research suggests that quadriceps RTD may provide additional information beyond that provided by quadriceps strength, the associations among quadriceps RTD, jump performance, and vGRFs and loading rates during landing remain unknown in persons who have undergone ACL reconstruction.

The present study evaluated the prospective associations among quadriceps strength and RTD and single-leg hop for distance and single-leg vertical jump, as well as the vGRF and loading rate during landing from a vertical jump, in persons who had undergone ACL reconstruction. While the vGRF and loading rate provide an indication of the impact forces that occur during landing, common clinical performance measures, such as hop distance and jump height, provide a gross measure of athletic performance. We hypothesized that quadriceps strength and RTD would be independent predictors of the various measures of hopping and jumping performance.

METHODS

The present study included a sample of patients from a prospective cohort study that sought to identify the predictors of physical activity levels in persons who had undergone ACL reconstruction. Between November 2011 and April 2013, we recruited 100 patients who underwent unilateral ACL reconstruction with semitendinosus-gracilis autografts at Singapore General Hospital, Singapore. All patients underwent ACL reconstruction rehabilitation, which included early weight bearing, progressive quadriceps strength training, and neuromuscular retraining. Patients were excluded if they had a previous or concurrent posterior cruciate ligament injury; preoperative knee extension range-of-motion deficits greater than 10°; significant neck, back, or other nonrelated knee pain; or any medical conditions that could compromise physical function or affect their ability to complete testing.

All patients were scheduled for evaluation within a month before surgery and approximately 6 weeks and 6 months after surgery. The present study used data from a cohort of 70 patients with 6-week quadriceps measures as well as 6-month outcome measures (hop or vertical jump measures). Patients with missing data from either of the 2 time points were not included in the current analysis.

The final sample comprised patients with a mean ± SD age of 25 ± 6 years who were predominantly male (n = 60, 86%) (**TABLE 1**). Sixty-five patients participated in competitive sports (Tegner activity level of 7 and above) before ACL rupture. Patients included in the current study were similar to those who were excluded because of missing data (see the **APPENDIX**, available at www.jospt.org). The Singhealth Centralized Institutional Review Board approved the study, and all patients provided written informed consent.

TABLE 1 Demographics and Clinical Characteristics of the Study Participants (n = 70)*

Characteristic	Value
Age, y	25.4 ± 5.9 (21, 24, 29)
Sex (male), n (%)	60 (86)
Mass, kg	71 ± 14 (61, 69, 78)
Height, m	1.70 ± 0.06 (1.67, 1.72, 1.75)
Preinjury Tegner score	7.6 ± 1.1 (7, 7, 9)
Preoperative levels	
Hop for distance, cm	130 ± 37 (107, 136, 154)
Vertical jump, cm	9.6 ± 3.6 (7.2, 10.0, 12.6)
Normalized vGRF, N/J	40 ± 19 (29, 35, 47)
Loading rate, $N/J \cdot s^{-1}$	496 ± 215 (361, 424, 601)
6 wk post ACL reconstruction	
Quadriceps strength, Nm	119 ± 44 (84, 124, 149)
Normalized quadriceps strength, $Nm \cdot kg^{-1}$	1.7 ± 0.6 (1.2, 1.8, 2.1)
Quadriceps RTD, $Nm \cdot s^{-1}$	673 ± 327 (438, 684, 888)
Normalized quadriceps RTD, $Nm \cdot s^{-1} \cdot kg^{-1}$	9.6 ± 4.6 (6.4, 9.0, 12.9)
Quadriceps testing pain (0-10)	1.5 ± 2.1 (0.0, 0.0, 2.8)
6 mo post ACL reconstruction	
Hop for distance, cm	138 ± 42 (106, 145, 170)
Vertical jump, cm	8.8 ± 3.6 (5.9, 8.9, 11.2)
Normalized vGRF, N/J	43 ± 21 (31, 37, 50)
Loading rate, $N/J \cdot s^{-1}$	555 ± 305 (341, 498, 684)

Abbreviations: ACL, anterior cruciate ligament; RTD, rate of torque development; vGRF, vertical ground reaction force.
**Values are mean ± SD (25th, 50th, 75th percentile) unless otherwise indicated.*

Quadriceps Strength and RTD

At 6 weeks following ACL reconstruction, isometric quadriceps strength and RTD of the operated limb were assessed using a Biodex System 4 isokinetic dynamometer (Biodex Medical Systems, Inc, Shirley, NY). Patients were tested in a seated position, with the hip at 90° of flexion and straps placed across the waist and chest to stabilize the torso. The dynamometer pad was strapped to the anterior aspect of the shank, proximal to the ankle. The knee was positioned at 70° of flexion, and gravity compensation was performed by measuring the patient's passive limb weight. The patients were instructed to extend their knee as fast and forcefully as possible for 2 to 3 seconds, without any preceding countermovement, in response to an acoustic signal. One submaximal practice trial and 3 test trials with a 1-minute rest interval were performed. Although previous studies have recommended the use of familiarization sessions,[19] they were not incorporated in the present study, as the testing sessions were often scheduled on the same day as the standard clinical rehabilitation appointments. During testing, verbal encouragement was given, and visual feedback was provided using a real-time display of the force-time curves on a computer screen (without numerical values) to encourage the participants to maximize torque production.

Data were collected using a custom-written software program (LabVIEW 2010; National Instruments, Austin, TX). Data were sampled at 1000 Hz and filtered with a Coiflet 5 low-pass filter at 31.25 Hz. Although the current study used a standard clinical dynamometer that could have increased baseline noise over that produced by custom-built strain-gauge systems,[19] the outcome measure of peak RTD should be minimally affected by potential baseline noise, as peak RTD often occurs on the slope of the torque trace after the onset of contraction. For data analysis, a range of different filters were examined, and the Coiflet filter was chosen because it eliminated much of the baseline noise of the dynamometer but had a minimal effect on the remaining data. The selected low-pass filter was the best option for consistent selection of the peak RTD.

The raw force values (Newtons) were converted to torque by multiplying force by the distance from the dynamometer axis to the dynamometer pad (meters). Quadriceps strength was defined as the highest torque reading across the 3 trials (Newton meters). Quadriceps RTD was calculated as the change in torque over the change in time during the initial rise in force. The specific method employed for this study involved an iterative 50-millisecond window that scanned the torque trace to find the highest RTD across the trial (eg, samples 1 to 50, 2 to 51, 3 to 52, etc).

Quadriceps RTD was defined as the highest RTD across the 3 trials (Newton meters per second). The peak RTD typically occurred during the first 200 milliseconds of the contraction (**FIGURE**). Other methods of RTD calculation often define the onset of contraction; however, many arbitrary methods may be used to determine onset that can affect the RTD results.[19] The maximum or highest RTD was used in this study because it has fair to good reliability in young, healthy adults[20] and in older adults with hip osteoarthritis.[25]

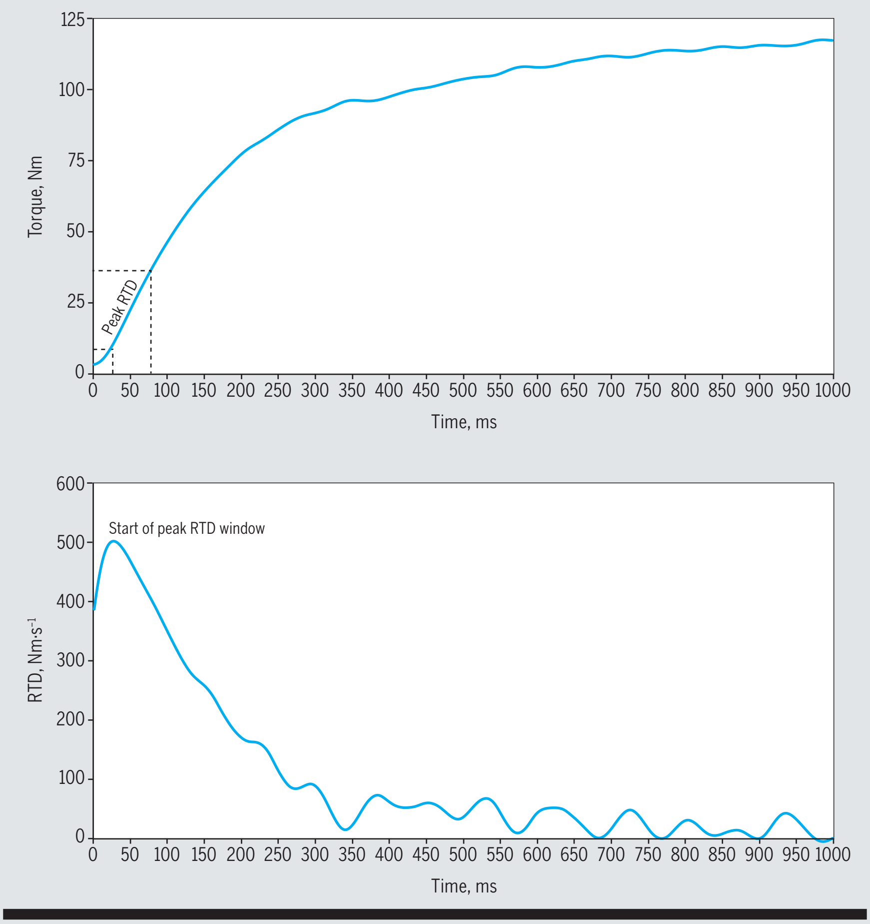

FIGURE. Representative torque-time curve with peak RTD and RTD-time curve with the start of the peak RTD window. The peak RTD occurred in different points of the curve for every contraction. Peak RTD is the 50-millisecond window with the highest RTD across the trial. In this example, the peak RTD occurs from 27 to 77 milliseconds (RTD, 506 $Nm \cdot s^{-1}$). Strength was calculated as the highest torque reading. Abbreviation: RTD, rate of torque development.

Clinical and Biomechanical Measures

Preoperatively and at 6 months after ACL reconstruction, each patient's hop and jump performance was assessed. The preoperative outcomes served as covariates, and the 6-month measures served as dependent variables.

Single-Leg Hop for Distance Test For the single-leg hop for distance test,[7] patients stood on 1 leg and performed a maximum hop for distance. Patients were instructed to hop as far as they could, with no restrictions on upper-body movement. Successful trials required a stable landing. Trials were considered unsuccessful if the patient exhibited additional movements of the foot upon landing, touched the ground with the contralateral limb, or lost balance.[18] Each patient performed 2 submaximal practice trials followed by 3 test trials on the ACL-reconstructed limb. The highest measurement was used for statistical analysis.

Vertical Jump Test The single-leg vertical countermovement jump (on the ACL-reconstructed limb) was performed with the patient standing on a force platform (AccuPower; Advanced Mechanical Technology, Inc, Watertown, MA).[24] Patients were required to place their hands on their hips and instructed to jump as high as they could while maintaining a stabilized landing. The criterion for a successful hop for distance trial also was applied to the vertical jump test. One practice trial and 2 successful trials were recorded, with a 30-second rest provided between jumps. Additional jumps were allowed if the patients felt they could improve performance.

Data were collected with custom-written software (LabVIEW 2010; National Instruments) at 1000 Hz. A 62.5-Hz Symlet-8 wavelet filter was applied to the force data. The 3 outcome measures taken from the vertical jump trials were jump height, vGRF, and average loading rate.[12,21] Vertical jump height was calculated using the following formula: $0.5g(t/2)^2$, where g is gravity and t is flight time in seconds. The peak vGRF recorded during landing (Newtons) was normalized to potential energy (Joules). Potential energy was calculated by multiplying the weight of the patient (Newtons) by the vertical jump height (meters). The loading rate was calculated by dividing the normalized vGRF (Newtons per Joules) by the time taken from the initial landing to peak vGRF (seconds). Initial landing was defined when the force exceeded 10 N. The highest vertical jump height trial was used for statistical analysis, with the vGRF and loading rate taken from the same trial.

Covariates

To adjust for the effects of confounding variables, we identified 8 covariates a priori: age, sex, weight, knee pain intensity during quadriceps testing, and preoperative levels of outcome (hop for distance, vertical jump height, vGRF, and loading rate). Pain intensity was assessed immediately following quadriceps testing. Specifically, patients were asked to rate their knee pain intensity on an 11-point numeric pain scale, with 0 indicating "no pain" and 10 indicating the "worst pain ever experienced." Our regression models (described later), each comprising 2 quadriceps measures and 5 covariates, required a minimum of 7 degrees of freedom. Based on the guideline of at least 10 patients per degree of freedom,[10] a multivariable model with a complexity of 7 degrees of freedom can be reliably fitted if its effective sample size is at least 70 patients.

Statistical Analysis

We used means with standard deviations and medians with interquartile ranges to present continuous variables and frequencies with percentages to present categorical variables. The association between quadriceps strength and RTD was estimated using Spearman's rank correlation.

We used a multivariable linear regression model for the hop distance and jump height outcomes and a proportional odds regression model[10] for the vGRF and loading-rate outcomes to evaluate the associations among quadriceps measures and future hop and jump outcomes, while adjusting for age, sex, weight, pain intensity during quadriceps testing, and preoperative outcome levels. Of note is our use of proportional odds regression to analyze the kinetic measures, as no suitable transformation achieved normality of residuals required for ordinary least-squares regression, proportional odds regression being applicable to skewed continuous dependent variables.[10] Given that quadriceps strength and RTD were quantified on different scales, we estimated mean differences and odds ratios (ORs) for an interquartile range increment of each quadriceps measure to facilitate a more standardized and clinically meaningful comparison of effect sizes.[10]

To assess the performance (global goodness of fit) of the various models, we computed the R^2 and the likelihood ratio chi-square statistics. To compare the explanatory value of quadriceps strength and RTD, we used the partial F test (for the hop and vertical jump outcomes) and the likelihood ratio chi-square test (for the vGRF and loading-rate outcomes) to assess whether quadriceps strength added incremental explanatory value to a model that included both quadriceps RTD and covariates, and vice versa.[10]

We assessed the appropriateness of all models using residual plots. Overall, 4 patients had 1 missing covariate value; hence, to minimize selection bias from missing data, we performed predictive-mean-matching multiple imputation with 30 replications.[10,11] All analyses were performed in R software, Version 3.2.3 (http://www.r-project.org).

RESULTS

During quadriceps testing, the mean knee pain rating was low (1.5 points), and quadriceps strength and RTD correlated strongly with each other (Spearman rho = 0.79).

The results from the multivariable regression analyses examining 6-week quadriceps strength and RTD as predictors of 6-month single-leg hop and vertical jump performance are presented in **TABLE 2**. To facilitate the interpretation and comparison of the results, the effect sizes for quadriceps strength and RTD were expressed in terms of an increase of 1 interquartile range in the value of the quadriceps measure. Adjusting for covariates, quadriceps strength and RTD were independently associated with all outcome measures ($P \leq .04$). Both greater quadriceps strength and RTD were associated with greater (1) hop distance per interquartile range increase in quadriceps strength (27.3 cm; 95% confidence interval [CI]: 11.8, 42.8 cm) and RTD (23.0 cm; 95% CI: 8.0, 37.9 cm) and (2) jump height per interquartile range increase in quadriceps strength (1.76 cm; 95% CI: 0.21, 3.32 cm) and RTD (2.03 cm; 95% CI: 0.69, 3.37 cm). Lower quadriceps strength and RTD were associated with greater odds of increased vGRF and loading-rate levels (2.2 to 4.6 times greater odds of increased vGRF or loading-rate levels per interquartile range decrease in quadriceps strength and RTD).

TABLE 3 shows the R^2 and likelihood ratio chi-square statistics for all models. For the clinical measures of hop distance and vertical jump height, quadriceps strength had significantly higher R^2 for the hop distance model than did quadriceps RTD (P = .05), whereas quadriceps RTD had higher R^2 for the vertical jump model (P = .05). For the kinetic measures, after adjusting for covariates, quadriceps RTD added statistically significant predictive value to the vGRF model that included quadriceps strength ($P<.01$). Although quadriceps RTD had a higher likelihood ratio chi-square value than quadriceps strength for the loading-rate model, the incremental predictive value of quadriceps RTD over quadriceps strength was not statistically significant (P = .17).

DISCUSSION

In this prospective study, we found that greater quadriceps strength and RTD at 6 weeks post ACL reconstruction were associated with greater single-leg hop distance and vertical jump height performance at 6 months post ACL reconstruction. Quadriceps strength and RTD at 6 weeks post ACL reconstruction were also associated with lower vGRFs and average loading rates while landing from a vertical jump. Furthermore, single-leg hop distance was more strongly associated with quadriceps strength than with quadriceps RTD. In contrast, vertical jump height and vGRF were more strongly associated with quadriceps RTD than with quadriceps strength. Finally, lower quadriceps strength and RTD at 6 weeks following ACL reconstruction were prospectively associated with higher loading-rate levels at 6 months following ACL reconstruction, with a similar magnitude of association (approximately 2.2 and 2.5 times greater odds of increased loading-rate levels per interquartile range decrease in quadriceps strength and RTD, respectively).

Both quadriceps strength and RTD were found to be predictors of future hop distance and jump height. Although several previous studies have shown associations of quadriceps strength and RTD with hop and jump performance,[4,8,15,17,24,27] the prospective associations of quadriceps RTD with these clinical measures have not been examined in patients who have undergone ACL reconstruction. Our results are consistent with the fact that maximal-effort hopping and jumping involve, among other factors, rapid and powerful contractions of the lower extremity muscles. Interestingly, in mutually adjusted analyses (**TABLE 3**), quadriceps strength had greater explanatory value than quadriceps RTD in predicting hop distance, whereas quadriceps RTD had greater explanatory value in predicting jump height. The mechanism responsible for these varied associations is uncertain but may be related to our test procedures. In keeping with clinical practice and previous research protocols,[1,3,28] patients were allowed to move their arms

TABLE 2 Associations of Quadriceps Strength and RTD at 6 Weeks Post ACL Reconstruction With Single-Leg Hop and Vertical Jump Performances at 6 Months Post ACL Reconstruction*

		Hop for Distance		Vertical Jump		Normalized vGRF		Loading Rate	
	25th-75th Percentile	Difference†‡	P Value	Difference†‡	P Value	OR†§	P Value	OR†§	P Value
Strength, Nm	84-149	27.3 (11.8, 42.8)	<.001	1.76 (0.21, 3.32)	.03	3.10 (1.29, 7.42)	.01	2.22 (1.02, 4.82)	.04
RTD, Nm/s	438-888	23.0 (8.0, 37.9)	<.01	2.03 (0.69, 3.37)	<.01	4.64 (2.04, 10.56)	<.001	2.46 (1.18, 5.09)	.02

Abbreviations: ACL, anterior cruciate ligament; OR, odds ratio; RTD, rate of torque development; vGRF, vertical ground reaction force.
**Results shown are from linear regression models (hop distance and vertical jump) or proportional odds regression models (normalized vGRF and loading rate). All analyses were adjusted for age, sex, weight, knee pain during testing, and preoperative outcome measures.*
†Values in parentheses are 95% confidence interval.
‡Adjusted differences in hop distance or vertical jump reflect a comparison between the 75th and the 25th percentile values of each quadriceps measure. For example, other variables being equal, patients with quadriceps strength of 149 Nm (75th percentile) hopped, on average, 27 cm (95% confidence interval: 12, 43 cm) farther than patients with quadriceps strength of 84 Nm (25th percentile).
§ORs estimate the odds of greater normalized vGRF and loading rate at the 25th versus the 75th percentile values of each quadriceps measure. For example, other variables being equal, patients with quadriceps strength of 84 Nm (25th percentile) had, on average, 3.1 times (95% confidence interval: 1.3, 7.4 times) the odds of having a greater normalized vGRF relative to patients with quadriceps strength of 149 Nm (75th percentile).

TABLE 3 Predictive Value of Quadriceps Strength and RTD at 6 Weeks Post ACL Reconstruction for Single-Leg Hop and Vertical Jump Performances at 6 Months Post ACL Reconstruction*

	Hop for Distance		Vertical Jump		Normalized vGRF		Loading Rate	
	R^2	*P* Value†	R^2	*P* Value†	χ^2 (%)‡	*P* Value†	χ^2 (%)‡	*P* Value†
Strength	0.46	.0499	0.33	.54	39.5 (85)	.84	30.1 (94)	.64
RTD	0.44	.27	0.37	.0495	46.7 (100)	<.01	31.7 (99)	.17
Strength plus RTD	0.47	...	0.37	...	46.7 (100)	...	32.0 (100)	...

Abbreviations: ACL, anterior cruciate ligament; RTD, rate of torque development; vGRF, vertical ground reaction force.
**Results shown are from linear regression models (hop distance and vertical jump) or proportional odds regression models (normalized vGRF and loading rate). All analyses were adjusted for age, sex, weight, knee pain during testing, and preoperative outcome measures.*
†P value from a partial F test (hop distance and vertical jump) or likelihood ratio chi-square test (normalized vGRF and loading rate) for nested models evaluating the incremental value of quadriceps strength over quadriceps RTD, adjusting for covariates, and vice versa.
‡Expressed as a proportion of the likelihood ratio chi-square value of a full model that included the covariates, quadriceps strength, and quadriceps RTD.

freely during the single-leg hop test. In contrast, during the vertical jump test, patients were instructed to keep their arms akimbo to reduce the contributions of arm movements to jump performance. Accordingly, given the theorized role of quadriceps RTD in dynamic knee stability, the contribution of free arm movement to body stability during the hopping task might have reduced the association between quadriceps RTD and hop distance.[2] These explanations are speculative, and future studies are needed to compare the associations of quadriceps performance with hop and jump tasks performed with free or restricted arm movement. Nevertheless, the differential results observed do support the view that quadriceps strength and RTD may have complementary functions.

In contrast to previous studies, we compared the associations of quadriceps strength and RTD not only with clinical hop or jump measures but also with kinetic measures of landing performance. While quadriceps strength and RTD were predictors of vGRF and loading rate during landing from a vertical jump, quadriceps RTD had greater value in predicting vGRF levels. A plausible explanation for this finding is that the impact-absorption phase of a vertical jump occurs over approximately 150 milliseconds,[22] such that the knee musculature has to control and attenuate impact forces over a short period. Thus, quadriceps RTD may have a stronger influence on force attenuation and neuromuscular knee control than quadriceps strength. These findings, taken together with a high correlation between quadriceps strength and RTD (Spearman rho = 0.79), support the notion that quadriceps strength and RTD may have complementary and partially differing influences on jumping tasks.

Our finding of an association between quadriceps strength and kinetic measures generally is in agreement with Schmitt et al,[26] but in contrast to Ithurburn et al.[14] Schmitt et al[26] found that, in 77 participants who had undergone ACL reconstruction, greater between-limb asymmetry in isometric quadriceps strength was associated with greater asymmetry in peak vGRF and peak loading rates. Ithurburn et al,[14] however, did not find similar associations in their sample of 103 participants. That said, important methodological differences prevent direct comparisons with the present study, including the mode of vertical jump assessment (single-leg vertical countermovement jump versus single-leg vertical drop jumps) and the study design (prospective cohort versus cross-sectional design). Accordingly, further studies are needed to confirm and explain our findings.

Our study has several clinical implications. As measurements of quadriceps RTD preceded and were associated with the various hop/jump measurements, our findings suggest that early interventions aimed at promoting rapid muscle contractions may improve future hop/jump performance and reduce the between-limb asymmetries in vGRF and loading-rate measures often observed in patients with ACL reconstruction.[21,23] That said, as the present study is a secondary analysis of this cohort, we did not have contralateral quadriceps measurements and could not define meaningful side-to-side RTD deficits. In addition, given that patients who have undergone ACL reconstruction are at increased risk for premature knee osteoarthritis, perhaps as a result of abnormal knee loading, findings from this study provide potential justification for further studies evaluating the role of quadriceps strength and RTD in the development of premature osteoarthritis.

Our study had several limitations. First, our sample was composed predominantly of men, which limits the generalizability of the results to women. Second, we did not have data on quadriceps performance and hopping/jumping measures for all eligible patients; however, excluded patients did not differ significantly from the enrolled patients based on preoperative clinical demographics (**APPENDIX**). Third, our vGRF and loading-rate measures are not direct measures of knee loading. Fourth, we obtained quadriceps measurements at only 1 time point and could not assess the influence of longitudinal changes in quadriceps measurements on hop and jump performance. Future studies are needed to establish time trends and determine whether these longitudinal associations vary in response to different rehabilitation strategies. Fifth, the use of a standard isokinetic dynamometer could have increased the baseline noise of the torque signal and impacted the results.[19] However, this limitation would have had a minimal effect on our results, as the peak RTD that was computed in the present study was not dependent on the discrete time onset of contraction, which would be more affected by baseline noise. Peak RTD was calculated as the highest reading in a 50-millisecond window across the recorded trials, which may be a highly variable measurement between trials. Although average RTD may provide a more reliable measure, peak RTD was used to provide a measure of the quickest contraction each participant could produce. Additionally, a familiarization session was not able to be provided to participants due to the timing of their research and clinical appointments, which might have affected the RTD results.

CONCLUSION

Quadriceps strength and RTD are independent predictors of future hop and jump performance in patients who have undergone ACL reconstruction. Our findings add to the growing body of literature demonstrating that quadriceps strength and RTD may have complementary but distinct effects on physical function and neuromuscular knee control in patients post ACL reconstruction. ◉

KEY POINTS

FINDINGS: Quadriceps strength and rate of torque development (RTD) are complementary but distinct predictors of future hopping and jumping performance in patients following anterior cruciate ligament reconstruction. Specifically, single-leg hop distance was associated more closely with quadriceps strength than with quadriceps RTD, and vertical jump height and vertical ground reaction force measures were associated more closely with quadriceps RTD than with quadriceps strength.

IMPLICATIONS: These findings may contribute to improved rehabilitation of patients who are at risk for poor jumping/hopping performance and abnormal knee loading.

CAUTION: Quadriceps measurements were obtained at only 1 time point; hence, the study could not assess the influence of longitudinal changes in quadriceps strength and RTD on hop and jump performance.

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APPENDIX

BASELINE CHARACTERISTICS OF INCLUDED AND EXCLUDED PARTICIPANTS*

Characteristic	Included Participants (n = 70)	Excluded Participants (n = 30)	*P* Value†
Age, y	25.4 ± 5.9 (21, 24, 29)	27.1 ± 5.9 (22, 28, 31)	.15
Sex (male), n (%)	60 (86)	23 (77)	.27‡
Body weight, kg	71 ± 14 (61, 69, 78)	72 ± 18 (54, 76, 85)	.68
Height, m	1.70 ± 0.06 (1.67, 1.72, 1.75)	1.71 ± 0.09 (1.67, 1.71, 1.78)	.93
Preinjury Tegner score	7.6 ± 1.1 (7, 7, 9)	7.6 ± 1.2 (7, 7, 9)	.96
Preoperative hop for distance, cm	130 ± 37 (107, 136, 154)	120 ± 41 (88, 128, 151)	.35

**Values are mean ± SD (25th, 50th, 75th percentile) unless otherwise indicated.*
†Wilcoxon test unless otherwise indicated.
‡Pearson chi-square test.