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original research

Knee-Extension Torque Variability and Subjective Knee Function in Patients With a History of Anterior Cruciate Ligament Reconstruction

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Context: When returning to physical activity, patients with a history of anterior cruciate ligament reconstruction (ACL-R) often experience limitations in knee-joint function that may be due to chronic impairments in quadriceps motor control. Assessment of knee-extension torque variability may demonstrate underlying impairments in quadriceps motor control in patients with a history of ACL-R.

Objective: To identify differences in maximal isometric knee-extension torque variability between knees that have undergone ACL-R and healthy knees and to determine the relationship between knee-extension torque variability and self-reported knee function in patients with a history of ACL-R.

Design: Descriptive laboratory study.

Setting: Laboratory.

Patients or Other Participants: A total of 53 individuals with primary, unilateral ACL-R (age = 23.4 ± 4.9 years, height = 1.7 ± 0.1 m, mass = 74.6 ± 14.8 kg) and 50 individuals with no history of substantial lower extremity injury or surgery who served as controls (age = 23.3 ± 4.4 years, height = 1.7 ± 0.1 m, mass = 67.4 ± 13.2 kg).

Main Outcome Measure(s): Torque variability, strength, and central activation ratio (CAR) were calculated from 3-second maximal knee-extension contraction trials (90° of flexion) with a superimposed electrical stimulus. All participants completed the International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form, and we determined the number of months after surgery. Group differences were assessed using independent-samples *t* tests. Correlation coefficients were calculated among torque variability, strength, CAR, months after surgery, and IKDC scores. Torque variability, strength, CAR, and months after surgery were regressed on IKDC scores using stepwise, multiple linear regression.

Results: Torque variability was greater and strength, CAR, and IKDC scores were lower in the ACL-R group than in the control group ($P < .05$). Torque variability and strength were correlated with IKDC scores ($P < .05$). Torque variability, strength, and CAR were correlated with each other ($P < .05$). Torque variability alone accounted for 14.3% of the variance in IKDC scores. The combination of torque variability and number of months after surgery accounted for 21% of the variance in IKDC scores. Strength and CAR were excluded from the regression model.

Conclusions: Knee-extension torque variability was moderately associated with IKDC scores in patients with a history of ACL-R. Torque variability combined with months after surgery predicted 21% of the variance in IKDC scores in these patients.

Key Words: quadriceps muscle, motor control, neuromuscular, disability

Key Points

- Maximum knee-extension torque variability was moderately associated with International Knee Documentation Committee Subjective Knee Evaluation Form scores in patients who had undergone anterior cruciate ligament reconstruction.
- Torque variability combined with months after surgery predicted 21% of the variance in International Knee Documentation Committee Subjective Knee Evaluation Form scores in patients who had undergone anterior cruciate ligament reconstruction.
- When assessing quadriceps function in these patients, clinicians and scientists should consider including measures of knee-extension motor control, such as torque variability.

Anterior cruciate ligament reconstruction (ACL-R) is the primary surgical treatment for individuals experiencing disability after an anterior cruciate ligament (ACL) injury. Despite surgical intervention and rehabilitation, a large proportion of patients report long-term physical disability that is detrimental to physical activity levels.[1] A history of ACL-R is also associated with a greater risk for chronic degeneration of the articular tissues of the knee, which leads to early-onset osteoarthritis.[2,3] Posttraumatic changes in quadriceps motor function may be associated with long-term disability in patients who have had ACL-R.[4,5]

A wealth of evidence has suggested that ACL-R causes both immediate and long-term changes in quadriceps motor function, which can manifest as weakness,[6,7] inhibition,[6,8] and diminished power[9,10] and motor control.[11,12] Impaired quadriceps motor function is concerning to clinicians and scientists due to the primary role the quadriceps play in lower extremity locomotion, force attenuation, and functional stability about the knee. Deficient quadriceps motor function may contribute to abnormal movement strategies

Table 1. Anterior Cruciate Ligament-Reconstruction and Control Group Demographics[a]

Characteristic	Group: Anterior Cruciate Ligament Reconstruction (n = 53)	Control (n = 50)
Sex	27 men, 26 women	28 men, 22 women
	Mean ± SD	
Age, y	23.4 ± 4.9	23.3 ± 4.4
Height, m	1.7 ± 0.1	1.7 ± 0.1
Mass, kg[a]	74.6 ± 14.8	67.4 ± 13.2
Tegner Activity Scale score (range, 0–10)	6.8 ± 1.8	6.8 ± 1.8
Months after surgery	44.1 ± 29.9	Not applicable

[a] Indicates group difference ($P \leq .05$).

that patients with ACL-R demonstrate during walking,[13] jogging,[14] and landing.[15] Quadriceps motor dysfunction is commonly evaluated during knee-extension contractions. Weakness and inhibition, quantified as decreased magnitudes of peak torque and central activation, are the more frequently reported quadriceps motor impairments.[4,6–8,16,17]

Torque variability (ie, force steadiness, force control) is a measure of motor control that describes a patient's ability to produce smooth and steady muscle contractions and focuses on the quality of torque production rather than traditionally reported quantity. Researchers have identified diminished quadriceps muscle control in patients with ACL-deficient,[18,19] ACL-reconstructed,[12,19] and osteoarthritic[20,21] knees using measures of maximal and submaximal, isometric, and isokinetic knee-extension contractions. Assessments of muscle control, or the quality of muscle contractions, are seldom used in clinical settings; however, these measures may provide valuable insight into motor recovery and disability after ACL-R.

The relationship between poor quadriceps motor control and subjective knee-related function in patients with ACL-R is unknown. Therefore, the purpose of our study was to (1) identify differences in maximal isometric knee-extension torque variability between knees that have undergone ACL-R and healthy knees and (2) to evaluate the relationship between measures of knee-extension torque variability and self-reported knee function in patients who have undergone ACL-R.

METHODS

The primary independent variables in this descriptive laboratory study were torque variability (coefficient of variation), strength (normalized peak torque), central activation ratio (CAR) during maximal volitional and superimposed-burst (SIB) knee-extension contractions, and months after surgery. The dependent variable was the International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form score.

Participants

We analyzed 103 recreationally active adults who had previously participated in research studies in our laboratory.[22,23] *Recreationally active* was defined as exercising 3 to 5 times per week. Preliminary analyses included 55 participants who had undergone ACL-R; however, 2 participants were excluded due to excessive time since surgery (144 and 206 months); they presented as outliers compared with the cohort, so we included 53 participants who had undergone ACL-R in the final analyses. These 53 participants (27 men, 26 women) had undergone primary, unilateral ACL-R more than 6 months before testing (ACL-R group). Eligibility criteria for the ACL-R group were no restrictions placed on physical activity by a health care provider, no history of graft failure, and no complications after surgery (ie, infection, contracture). Fifty age-matched participants (28 men, 22 women) with no history of lower extremity joint injury or surgery acted as healthy controls (control group). Demographic characteristics of sex, age, height, mass, and Tegner Activity Scale (Tegner) score[24] were recorded for all participants (Table 1). All participants provided written informed consent, and the Institutional Review Board for Health Sciences Research at the University of Virginia approved this study.

Data Collection

We measured volitional and superimposed maximal isometric knee-extension torques using a Biodex System III dynamometer (Biodex Medical Systems Inc, Shirley, NY). Participants were seated with their hips and knees positioned at 85° and 90° of flexion, respectively, and the dynamometer arm was secured to the lower leg just superior to the malleoli. We instructed them to sit up tall with their back flat against the back of the Biodex chair and upper extremities placed across their chest. Two 7.5-cm × 13-cm electrodes were adhered to the skin over the quadriceps muscles. A Grass SS8 stimulator (Grass-Telefactor, West Warwick, RI) and Stimstoc stimulation isolation unit (Biopac Systems Inc, Goleta, CA) were used to deliver the SIB.[6] Before test trials, participants performed progressive isometric knee-extension practice trials for warm-up and to become familiar with the procedure. For testing, they completed three 3-second maximal voluntary isometric contractions (MVICs) while attempting to maintain a steady maximal torque plateau, and we delivered a manually triggered SIB using previously described methods.[6] Participants were provided a minimum 1-minute rest period between trials.

We calculated the number of months after surgery as the whole months that had elapsed from surgery to the testing date. All participants completed a paper version of the IKDC Subjective Knee Evaluation Form.

Data Processing

Torque data were digitized and low-pass filtered at 15 Hz. We calculated the mean and standard deviation of torque (Nm) from a 500-millisecond epoch during the maximal-contraction plateau. Torque variability was quantified using the following formula: Coefficient of variation = [(Torque standard deviation/Torque mean) × 100]. We calculated strength using the torque mean normalized by mass (Nm) and the following formula: Torque mean/Mass. The MVIC torque (Nm) and SIB torque (Nm) were calculated from a 200-millisecond time epoch before SIB and the maximum torque during the SIB, respectively. We calculated CAR using the following formula: [(MVIC torque/SIB torque) × 100]. Two time epochs were used in accordance with previously reported processing techniques[6] and a prelimi-

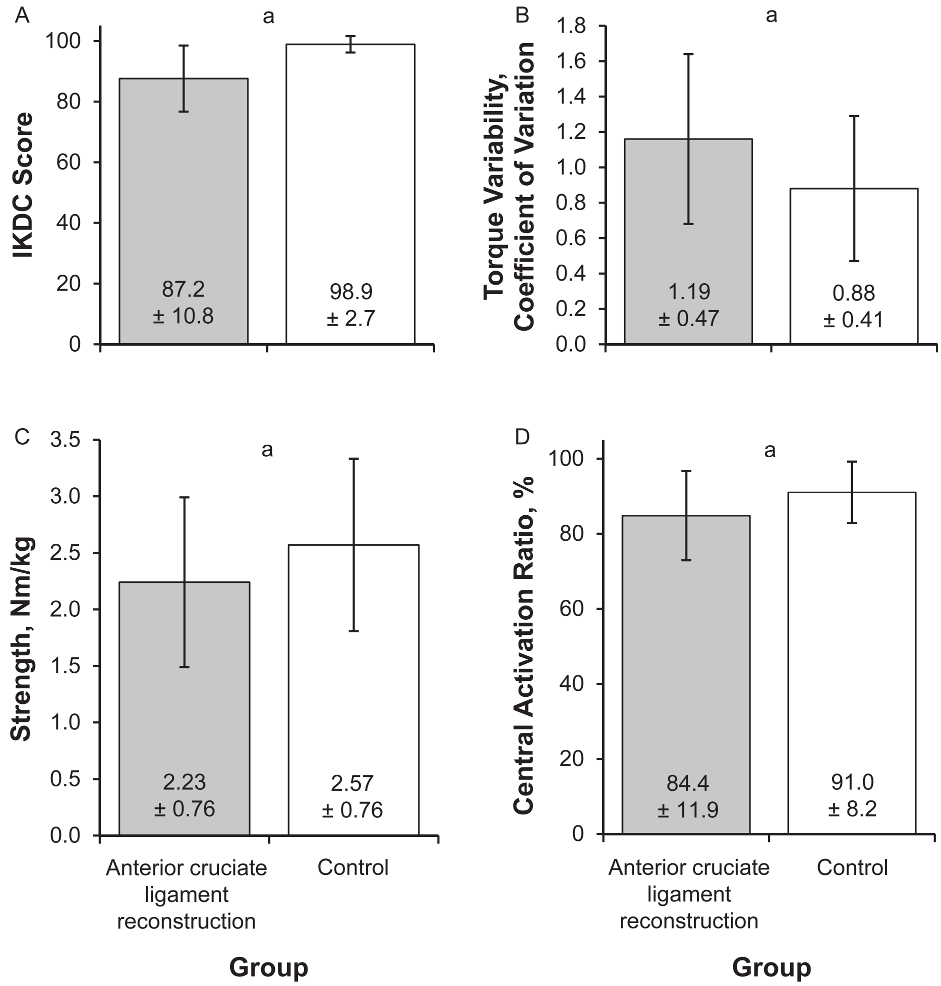

Figure 1. A, Mean International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form score (range, 0–100), B, Torque variability. C, Strength. D, Central activation ratio in anterior cruciate ligament-reconstruction and control groups. Error bars indicate ± standard deviation. [a] Indicates difference between groups ($P < .05$).

nary technique from our laboratory,[11] but time epochs typically overlapped.

Statistical Analysis

Group differences in demographics (sex, age, height, mass, physical activity), torque variability, strength, CAR, and IKDC scores were assessed using independent-samples *t* tests and the Pearson χ^2 test (sex).

We assessed Pearson *r* correlation coefficients among torque variability, strength, CAR, IKDC scores, and months after surgery in the participants who had undergone ACL-R. Each correlation coefficient (*r*) was interpreted based on a previously described classification using similar variables: 0 to 0.4 (*weak*), 0.4 to 0.7 (*moderate*), and 0.7 to 1.0 (*strong*).[25]

Multiple linear regression analyses were used to predict IKDC scores in the participants who had undergone ACL-R. We used stepwise selection to determine the variables included in the final model. Probability thresholds to enter or remove variables were set at 0.05 and 0.10, respectively. Variables entered into the model were torque variability, strength, CAR, and months after surgery. Based on a previously published sample-size estimating formula,[26] our sample was sufficient for the proposed analysis assuming a large effect size, a type 1 error rate of 5%, and power exceeding 80%. The α level was set at .05. We used SPSS (version 22; IBM Corporation, Armonk, NY) for statistical analysis.

RESULTS

Anterior Cruciate Ligament Reconstruction Versus Control

Demographics. Mass was greater in the ACL-R group than in the control group ($t_{101} = -2.63$, $P = .01$), but we observed no differences in sex ($\chi^2 = 0.26$, $P = .61$), age ($t_{101} = -0.10$, $P = .92$), height ($t_{101} = -1.76$, $P = .08$), or Tegner score ($t_{101} = -0.09$, $P = .93$) between groups (Table 1).

Quadriceps Function and IKDC Score. The ACL-R group demonstrated higher torque variability ($t_{101} = -3.49$, $P = .001$) and lower strength ($t_{101} = 2.28$, $P = .03$), CAR ($t_{101} = 3.22$, $P = .002$), and IKDC scores ($t_{101} = 7.45$, $P < .001$) than the control group (Figure 1).

Correlations

In the ACL-R group, we observed a weak negative correlation between IKDC scores and torque variability and a weak positive correlation between IKDC score and

Table 2. Correlation Coefficients Among International Knee Documentation Committee Subjective Knee Evaluation Form Score, Torque Variability, Strength, Central Activation Ratio, and Months After Surgery in Participants With Anterior Cruciate Ligament Reconstruction (n = 53)

Variable	International Knee Documentation Committee Subjective Knee Evaluation Form Score		Months After Surgery		Central Activation Ratio		Strength	
	r	*P*	*r*	*P*	*r*	*P*	*r*	*P*
Torque variability	−0.38[a]	.005	−0.01	.95	−0.41[a]	.002	−0.52[a]	<.001
Strength	0.28[a]	.04	0.20	.15	0.65[a]	<.001	1.0	
Central activation ratio	0.23	.09	0.17	.22	1.0			
Months after surgery	0.26	.06	1.0					

[a] Indicates correlation between 2 measures ($P < .05$).

strength (Table 2). The IKDC scores were not correlated with CAR or months after surgery in the ACL-R group. We observed no correlations between IKDC scores and CAR or months after surgery in the ACL-R group (Table 2).

Torque variability, strength, and CAR were all moderately correlated with each other in the ACL-R group (Table 2). We noted no correlations between torque variability, strength, or CAR and months after surgery (Table 2).

Multiple Regression

Torque variability, strength, CAR, and months after surgery were included in the stepwise regression analysis. The preliminary model, including only torque variability, predicted 14.3% of the variance in IKDC scores ($F_{1,51} = 8.50$, $P = .005$; Figure 2). The final model, including torque variability and months after surgery, predicted 21.0% of the variance in IKDC scores ($F_{1,50} = 6.64$, $P = .003$; Figure 2). Coefficients for torque variability ($\beta = -0.38$, $P = .004$) and months after surgery ($\beta = -0.26$, $P = .04$) were different. Adding months after surgery to the model resulted in an R^2 change of 6.7% (F change = 4.25, $P = .04$). Strength and CAR were excluded from the model.

DISCUSSION

Participants in the ACL-R group demonstrated higher maximal isometric torque variability and lower strength, CAR, and IKDC scores than the control group. Higher torque variability and lower strength were associated with greater self-reported knee-related disability in the ACL-R group. The combination of torque variability and months after surgery predicted about one-fifth (21%) of the variance in self-reported knee function in the ACL-R group. Torque variability alone accounted for 14.3% of the variance in IKDC scores.

Torque variability, which is the steadiness or quality of knee-extension torque production, describes the ability of muscles to control motor output. We observed greater maximal isometric torque variability in the ACL-R group than in the healthy control group, suggesting that quadriceps motor control may be impaired in patients with ACL-reconstructed knees. Less steady maximal isokinetic knee-extension contractions have been observed in participants with ACL-deficient[18,19] or ACL-reconstructed[19] knees than in healthy control participants, and less steady torque output has been associated with decreased single-legged–hop performance during timed and distance tasks.[18,19] Osteoarthritic knees have also demonstrated greater variability in torque[20,21] and poorer matching accuracy[20] than healthy knees during submaximal isokinetic knee-extension force-matching contractions, which were correlated with time to complete functional tasks.[20] Excessive unsteadiness of torque production may reflect changes in motor-output variability[27] due to disrupted sensorimotor pathways after ACL-R.[28] Evidence from animal models[29,30] has suggested that damage to articular tissues and receptors can alter sensory information from the knee. Sensory neurons synapse at multiple levels of the central nervous system and can directly alter motor output. In addition, antagonist hamstrings activation during knee-extension contractions may be responsible for aberrations in knee-extension torque.[12,19]

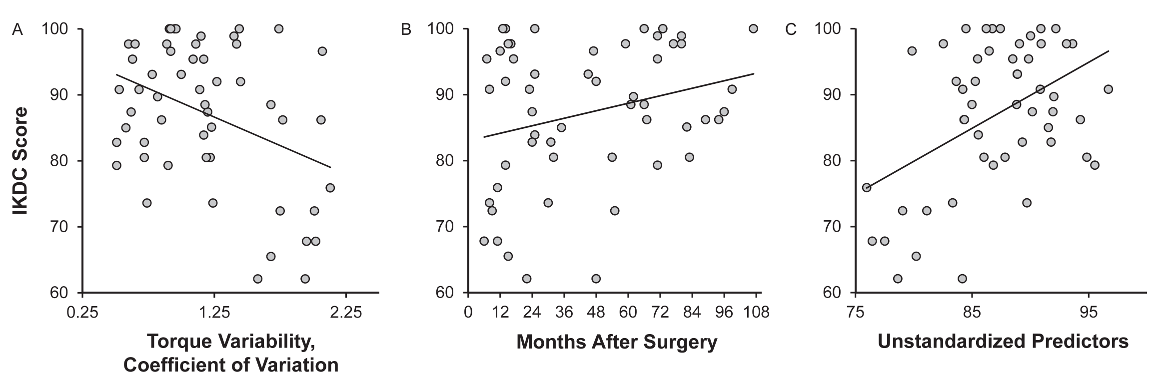

Figure 2. Scatter plots of the following: A, Torque variability. B, Months after surgery. C, Unstandardized predictor values (torque variability and months after surgery) versus the International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form score.

We observed an association between maximal isometric knee-extension torque variability and self-reported knee function in the ACL-R group. Of the 3 measures of quadriceps motor function that we reported, torque variability had the strongest association with knee disability, as measured by the IKDC score, and was the only variable included in the final prediction model. These findings might suggest that measures of torque variability account for a unique aspect of the maximal contraction that is more strongly associated with knee-related function; however, the results should be interpreted with caution considering that the correlations among all 3 measures of quadriceps motor function were moderate and that each of these variables was calculated using the mean torque from a maximal isometric knee-extension contraction. Pietrosimone et al[4] observed larger correlations ($r = 0.78$) and stronger predictability ($R^2 = 0.61$) between strength and IKDC scores in patients who had undergone ACL-R. Their ACL-R cohort reported levels of disability (IKDC score = 86.1 ± 8.9) and postoperative time (4.5 ± 3.4 years) similar to those in our study; yet their peak torque values (2.73 ± 0.57 Nm) were higher and their sample size (n = 15) was smaller.[4]

Multiple variables may contribute to subjective knee function after ACL-R, including psychological factors,[31] surgical technique,[32] associated knee damage,[33] activity demands,[34] and overall health of the patient.[35] The results of our predictive model indicated that as months after surgery increased (ranging from 6 to 107 months [8.9 years]), subjective knee function increased. However, we did not observe a correlation between IKDC scores and months after surgery ($r = 0.26$, $P = .06$). Quadriceps muscle dysfunction is a unique risk factor for poor subjective knee function because it is clinically modifiable through rehabilitation. In intervention studies, researchers[36,37] have demonstrated improved knee-extension torque control in older adults using light-load steadiness training, suggesting a potential avenue for rehabilitative intervention to address this impairment. Assessments and interventions targeting quadriceps motor control are not common in clinical or scientific settings, and an appreciation for the quality of muscle contractions may provide valuable information when evaluating muscle dysfunction.

Limitations of our study included the lack of direct measures of lower extremity physical function that have been used in previous studies and complementary neuromuscular measures, such as electromyography, that would provide insight into the clinical and functional role of quadriceps motor-output variability and underlying mechanisms. Additional limitations included the calculation of torque-variability measures from maximal isometric knee-extension contractions, a type of muscle contraction not common during normal daily activities. For convenience purposes, analyses for our study were performed on a series of previously collected MVIC and SIB trials as an initial investigation of quadriceps motor control in patients who had undergone ACL-R. We collected data using standard testing procedures for MVIC and SIB. Participants were instructed to produce a maximal contraction with a steady plateau. Contrary to investigations of submaximal force matching, we provided no visual target for contraction reference, which may have limited contraction control. Our use of a manually triggered SIB stimulus may be considered a limitation because the use of an automated torque-based stimulus may limit stimulus-timing error.[38] Despite these limitations, our results suggested that further study of quadriceps motor control in patients with ACL-R is warranted.

CONCLUSIONS

Maximal knee-extension torque variability was moderately associated with IKDC scores in patients who had undergone ACL-R. Torque variability combined with months after surgery predicted 21% of the variance in IKDC scores in patients who had undergone ACL-R. Clinicians and scientists should consider including measures of knee-extension motor control, such as torque variability, when assessing quadriceps function in these patients.

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