Quadriceps Strength and Corticospinal Excitability as Predictors of Disability After Anterior Cruciate Ligament Reconstruction

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Background: Disability is common in a proportion of patients after anterior cruciate ligament reconstruction (ACL-R). Neuromuscular quadriceps deficits are a hallmark impairment after ACL-R, yet the link between muscle function and disability is not understood. Purposes: To evaluate the ability of quadriceps strength and corticospinal excitability to predict self-reported disability in patients with ACL-R. Methods: Fifteen participants with a history of ACL-R (11 female, 4 male; 172 ± 9.8 cm, 70.4 ± 17.5 kg, 54.4 ± 40.9 mo postsurgery) were included in this study. Corticospinal excitability was assessed using active motor thresholds (AMT), while strength was assessed with maximal voluntary isometric contractions (MVIC). Both voluntary strength and corticospinal excitability were used to predict disability measured with the International Knee Documentation Committee Index (IKDC). Results: The overall multiple-regression model significantly predicted 66% of the variance in self-reported disability as measured by the IKDC index ($R^2 = .66$, $P = .01$). Initial imputation of MVIC into the model accounted for 61% ($R^2 = .61$, $P = .01$) of the variance in IKDC. The subsequent addition of AMT into the model accounted for an insignificant increase of 5% ($\Delta R^2 = .05$, $P = .19$) in the prediction capability of the model. Conclusions: Quadriceps voluntary strength and cortical excitability predicted two-thirds of the variance in disability of patients with ACL-R, with strength accounting for virtually all of the predictive capability of the model.

Keywords: maximal contraction, knee, transcranial magnetic stimulation

Injury to the anterior cruciate ligament (ACL) is common, occurring in 250,000 Americans each year. Treatment, including ligament reconstruction (ACL-R) and rehabilitation, has an estimated annual cost of approximately $3 billion. While surgical and rehabilitative advances have been employed to improve ACL-R outcomes, a proportion of patients report long-term postoperative self-reported disability related to the injured joint. In addition, history of ACL-R may increase the risk of chronic joint degeneration or posttraumatic knee osteoarthritis. There is increasing evidence that neuromuscular deficits may contribute to chronic joint dysfunction in people with ACL-R.

Quadriceps weakness is a common consequence of ACL-R, and regaining quadriceps function is usually a major focus of postsurgical therapeutic rehabilitation. Unfortunately, quadriceps strength deficits seem to persist long after therapeutic interventions have ended. The inability to generate appropriate quadriceps force may influence lower extremity biomechanics associated with energy attenuation at the knee. Recent literature suggests that these altered biomechanics may be a factor in hastening the progression of knee-joint degeneration after ACL-R. The potential biomechanical implications of decreased quadriceps function provide a compelling link to how muscular deficits may influence disability in people with ACL-R.

Factors contributing to disability after lower extremity injury are multifaceted and involve both physiological and psychological components. The International Knee Documentation Committee (IKDC) questionnaire has been found to be a valid and reliable measure to evaluate self-reported disability in patients with ACL injury. The ability to develop successful therapeutic interventions to improve disability in patients with ACL-R is highly reliant on effectively targeting impairments that are influential to altering disability. Recent investigations have found a strong association between quadriceps strength and self-reported knee stability in patients with osteoarthritis; however, there is a gap in the literature regarding how quadriceps strength associates with function in patients with ACL-R. Knowledge of the relationship between quadriceps dysfunction and self-reported disability in patients with ACL-R would benefit the advancement of
rehabilitative strategies that will increase the quality of life after ACL-R.

While quadriceps muscle weakness after ACL-R is documented,\(^7,8\) the underlying cause of this weakness is not clearly understood. Recent systematic reviews have found that neural activation of the quadriceps is diminished in ACL-R patients,\(^9\) suggesting that muscle weakness may be a product of underlying neural impairments. Additional evidence suggests that descending corticospinal excitability pathways, influential in generating voluntary muscle contractions, differ in people with ACL injury compared with healthy controls.\(^15\) While early investigations are showing that corticospinal excitability may play an influential role in altering muscle function,\(^15,16\) it is unclear how it affects patient-oriented outcomes of function. Currently, there is no substantial evidence that evaluates the relationship between self-reported disability and measures of voluntary quadriceps strength and corticospinal excitability. Therefore, the purpose of this study was to evaluate the ability of voluntary quadriceps strength, as measured by maximal voluntary isometric contractions (MVIC), and cortical excitability, as measured by active motor thresholds (AMT), to predict self-reported disability, using the IKDC, in patients with ACL-R.

**Methods**

This retrospective descriptive study was part of a larger case-control experiment and assessed 15 patients with a history of unilateral ACL-R. All participants were recruited from the university community through posted advertisements or word of mouth. All were required to be cleared by an orthopedic surgeon for participation in all activities without any restrictions before being admitted into the study. Level of activity was assessed with the Tegner activity level scale.\(^17\) We excluded any person with multiple ligament tears or knee surgeries other than ACL-R in either limb. In addition, all included participants were free from neurological or muscular disease; were not prescribed any medication that altered neurological function; had no history of brain/cranial surgeries, migraines, seizures, or concussion in the past 6 months; and were not currently pregnant. All outcome measures (IKDC, MVIC, and corticospinal excitability) were assessed on the same day in a 2-hour testing session. Participants were instructed not to consume caffeine on the day that they would be tested. All participants provided written informed consent using a form approved by the institutional review board before testing.

**Experimental Procedures**

During both MVIC and corticospinal testing, participants were seated in a dynamometer (Biodex System II Pro dynamometer, Biodex Medical Systems, Shirley, NY) with hips flexed to 85° and knees flexed to 90°. A padded Velcro strap was secured around the tibia and fibula at the height of the gastrocnemius–soleus muscle-belly junction to attach the dynamometer arm to the patient’s limb. The skin over the oblique portion of the vastus medialis was shaved, debrided, and cleaned with alcohol before application of the electromyography (EMG) electrodes. Disposable 10-mm pregelled Ag/AgCl electrodes (Biopac Systems, Inc) were applied, and the signal was amplified with a gain of 1000 (EMG100C Biopac Systems, Goleta, CA) before being digitally converted with a 16-bit data-acquisition system (MP150, Biopac Systems Inc). EMG signal was collected at 2 kHz with a common-mode rejection ratio of 110 dB, a noise voltage of 0.2 µV, and an input impedance of 1 MΩ. Two EMG electrodes were adhered 1.75 cm apart on the greatest bulk of the oblique portion of the vastus medialis at a 55° angle as previously reported.\(^18\) The reference electrode was positioned on the medial malleolus of the nondominant leg. Acqknowledge Biopac Software (Biopac Version 3.7.3 Goleta, CA) was used to visualize the EMG signal. Analog torque signal from the dynamometer was transmitted to a separate analog-to-digital converter via a custom-made cable. An in-house torque-acquisition and -visualization program collected torque signal at 150 Hz and was additionally projected onto a 20-in monitor for easy visualization by the participants.

**MVIC**

Participants performed a graded warm-up on the dynamometer to ensure they were able to maximally produce isometric knee-extension contractions.\(^19\) They performed practice knee-extension MVICs, 60 seconds apart, until the investigator was confident that each subject was able to exert maximal effort. The investigator determined that maximal effort was reached when torque outputs from subsequent practice trials did not increase more than 5 Nm. The investigator averaged the maximal outputs from the last 2 practice trials and calculated an MVIC target line that was 10% higher than the averages of the last 2 practice trials. A red target line was depicted on the collection monitor that represented torque output 10% above what the participants produced in the practice trials. Participants were able to visualize the magnitude of their exerted force and were instructed to try to produce enough force to move the exerted force above the red target line. They were unaware that reaching this target line was an unattainable goal; therefore, it encouraged maximal effort from participants. During testing, 2 separate MVICs were performed with consistent verbal encouragement, with the investigator using phrases such as *kick harder*. MVICs were not required to reach the target line but were only considered acceptable if the exerted force was at least higher than the mean force of the 2 highest practice trials used to calculate the target line. Rest periods of no less than 60 seconds separated...
the trials. The highest MVIC peak force of the 2 trials was used for data analysis.

**Corticospinal Excitability Testing**

During cortical excitability testing, participants were positioned exactly the same as during the MVIC testing. During these testing procedures, they wore a Lycra swim cap (Sprint Aquatics, Rothhammer International Inc, San Luis Obispo, CA) and earplugs (Aearo Co, Indianapolis, IN) to muffle the sound of the transcranial magnetic stimulation. Two landmark lines were drawn on the swim cap; one sagittally separating hemispheres and the other intersecting the sagittal line, coronally at the external auditory meatus. A MagStim model 200 (MagStim Company, Ltd, Wales, UK) was used to deliver a single magnetic pulse with a possible strength of 2 Teslas, yet the double-cone coil configuration only allows for a maximum of 70% of the stimulation (1.4 Teslas). During testing, participants performed an isometric knee extension at 90° of knee flexion at a normalized intensity of 5% of their MVIC. Before each stimulus, the investigator instructed the participant to exert enough force to meet a target line that was visualized on the monitor. No verbal encouragement was given during contractions.

The double-cone coil was moved anterior to posterior over the vertex of the skull, using the lines drawn on the swim cap for reference, while the investigator applied a magnetic stimulus of a constant intensity until the largest peak-to-peak motor-evoked potential in the vastus medialis of the injured limb was found. This point was denoted on the swim cap with a felt-tip marker and used as the point for stimulation during AMT testing. Vastus medialis AMTs were established by decreasing the magnetic stimulus by 5% until no motor-evoked potential could be elicited. Then the percentage of magnetic stimulation was increased by 1% until 5 out of 10 consecutive stimuli produced a measureable motor-evoked potential (>100 μV). The AMTs are expressed as a percentage of 2 Teslas. Higher AMTs indicate that more magnetic energy was needed to evoke a motor potential, thus representing higher thresholds and low corticospinal excitability. Conversely, lower AMTs depict less magnetic energy needed to excite neural tissue and cause an evoked potential, representing a high corticospinal excitability.

**IKDC Index**

The IKDC is a valid and reliable tool to assess self-reported disability in people with ACL injury. Participants were provided a quiet room with a desk to complete the IKDC form and were allowed to ask the investigator to clarify any questions they had about the survey instrument. On completion of the questionnaire, a single investigator calculated scores and input them into a spreadsheet. IKDC scores ranged from 0 to 100, with 100 indicating no disability.

**Statistical Analysis**

Means and standard deviations were calculated for demographics and main outcome measures (Table 1). Simple Pearson product–moment correlations were performed between predictor variables of MVIC and AMT and the dependent variable of IKDC score. In addition, we assessed the correlation between the 2 predictor variables (MVIC and AMT). We classified correlation coefficients \( r \) of 0–.4 as weak, .4–.7 as moderate, and .7–1.0 as strong. Furthermore, we used a stepwise hierarchical multiple-linear-regression analysis to examine the amount of variance in IKDC scores that could be explained by the variance in MVIC and AMT measures. The order in which the predictor variables (MVIC and AMT) were entered into the regression model was determined by the magnitude of the individual simple correlations. The total \( R^2 \) of the model, as well as the change in \( R^2 \) to the model from the addition of each predictor variable, was analyzed. The level of significance was established a priori at \( P \leq .05 \). All statistical analyses were performed with SPSS for Windows (version 17.0; SPSS, Chicago, IL).

**Results**

Means and standard deviations for demographics and main outcome measures can be found in Table 1. A positive, strong, and statistically significant correlation was found between MVIC and IKDC (\( r = .78, P = .001 \)), while a negative weak correlation was found between AMT and IKDC (\( r = -.24, P = .38 \)). Furthermore, there was a nonsignificant weak correlation (\( r = .18, P = .492 \)) found between the 2 predicting variables, AMT and MVIC. The overall multiple-regression model significantly predicted 66% of the variance in self-reported disability.

**Table 1 Participant Demographics**

<table>
<thead>
<tr>
<th>Demographic Measure</th>
<th>Measure</th>
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<tbody>
<tr>
<td>Height</td>
<td>172.3 ± 9.8</td>
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<tr>
<td>Mass</td>
<td>70.4 ± 17.5</td>
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<tr>
<td>Tegner Scale</td>
<td>6.6 ± 2.2</td>
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<tr>
<td>Months postinjury</td>
<td>54.4 ± 40.9</td>
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<tr>
<td>IKDC Index</td>
<td>86.1 ± 8.9</td>
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<tr>
<td>Quadriceps MVIC/kg of body mass</td>
<td>2.73 ± 0.57</td>
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<tr>
<td>Quadriceps AMT (%)</td>
<td>33.2 ± 12.05</td>
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Abbreviations: IKDC, International Knee Documentation Committee; MVIC, maximal voluntary isometric contraction; AMT, active motor threshold.
disability as measured by the IKDC index ($R^2 = .66$, $P = .01$; $IKDC = 0.78 \text{MVIC} - 0.24 \text{AMT} + 58.89$). Initial input of MVIC into the model accounted for 61% ($R^2 = .61$, $P = .01$) of the variance in IKDC. The subsequent addition of AMT into the model accounted for a nonstatistically significant increase of 5% ($\Delta R^2 = .05$, $P = .19$) in the model’s prediction capability.

Discussion

Quadriceps strength and corticospinal excitability in combination were able to predict two-thirds (66%) of the variance in self-reported disability in people with ACL-R. Simple positive correlation coefficients suggest that increased voluntary strength relates with increased self-reported function ($r = .78$, $P = .001$). It is important to note that an increase in AMT is actually a decrease in cortical excitability, denoting that more of a stimulus is needed to evoke a similar response. Therefore we interpret the correlation between AMT and IKDC ($r = -.24$, $P = .38$) as increased corticospinal excitability relating to increased self-reported function. The correlations between strength and disability were strong, while relationships between corticospinal excitability and disability were found to be weak. Corticospinal excitability only improved the predictive model by 5%, so 61% of the variance in self-reported function was explained solely by quadriceps strength. This study provides evidence that strength in a single muscle group predicts self-reported function in a cohort of patients 8 to 134 months postreconstruction.

While surgical and rehabilitative techniques are continuously being improved, there is a proportion of ACL-R patients who still report disability years after surgery. A mean IKDC score of 86 out of a possible 100 was found in our study, suggesting that on average, participants reported a 14% deficit in self-reported function. Previous studies have reported similar IKDC values in ACL-R patients. It remains unknown from our data whether the magnitude of the reported disability is consistent from the time the patient is discharged from supervised medical care, or is cyclical, possibly peaking years after reconstruction. Future longitudinal investigations should aim to assess changes associated with quadriceps dysfunction and self-reported disability in serial years after ACL-R. Regardless, our current results indicate that voluntary quadriceps muscle strength alone predicts the majority of variance associated with disability in a somewhat diverse cohort of patients with ACL-R. The strong predictive capability of strength alone makes it easy to oversimplify the results of our predictive model, but it is important to understand that other factors not included in this analysis may still contribute to self-reported function in these patients.

Proper quadriceps function previously has been touted to moderate function in people with severe knee injuries, but it is also an influential factor in predicting mortality in patients with cardiopulmonary disease. Regaining optimal muscle function after ACL-R is a common clinical concern, and often the degree to which strength is restored has been used as a criterion for returning patients to participation in various activities. Recent reviews have chronicled a multitude of studies reporting quadriceps strength deficits after ACL injury and ACL-R. These deficits have been found to be present years after ACL-R, suggesting that muscle dysfunction may be a persistent impairment that cannot be overcome by a proportion of people with knee-joint injury. In addition, it seems that reconstruction of a ruptured ACL paired with conventional rehabilitation may not be sufficient to restore quadriceps muscle strength in all patients with ACL-R. The current data seem to suggest that the inability to regain maximal quadriceps strength is of substantial importance, as this factor appears to be a strong predictor of self-reported disability.

Previous authors have reported that history of combined meniscal injury, smoking, ACL-R revision, and female sex are factors that may increase the potential for disability or inactivity in ACL-R patients, yet little is known about how quadriceps muscle strength may relate to disability in this population. Previous studies have reported that quadriceps strength before reconstruction predicts function 2 years after reconstruction, suggesting that quadriceps strength gains before surgery may be vital for decreasing disability after surgery. Understanding the relative importance of targeting quadriceps strength gains in this population is critical, as many scientific and clinical resources are being employed to develop the most effective techniques to address persistent quadriceps weakness. Unfortunately, strength deficits are not easily reversible, leading some to suggest that a specialized therapy may be needed to regain quadriceps function after joint injury.

An emerging theory suggests that deficits originating in the central nervous system may have a substantial effect on neuromuscular function. Cortical and reflexive pathways are well known to be the primary generators of movement. There is evidence that corticospinal excitability of the quadriceps muscle is affected after ACL injury. Novel rehabilitative theories have suggested that specifically targeting neural dysfunction may improve patient outcomes after ACL-R. In an effort to evaluate both the mechanical-force-generation capability of the quadriceps and the neural capacity for excitement, we tested voluntary strength and corticospinal excitability, respectively. Decreased corticospinal excitability had a very weak association with decreased disability and provided only a weak contribution (5%) to the regression model predicting disability. While corticospinal excitability did not contribute substantially to predicting disability, it remains possible that other outcomes related to neuromuscular function may significantly contribute to muscle voluntary strength in predicting disability. Future studies may want to consider adding factors unrelated to neuromuscular control, such as history of smoking or concomitant knee injury, that have previously been found to predict disability.
Early investigations have suggested that corticospinal excitability may play an influential role in altering muscle function, thereby affecting voluntary strength.\(^{10,10}\) This is important when understanding the conclusions drawn from the regression analysis performed. Finding no additional contribution from corticospinal excitability may not necessarily mean it has no influence on self-reported disability; rather, it may already be accounted for when voluntary strength is added to the regression analysis. The insignificant contribution from corticospinal excitability to the overall regression model may be due to both predictor variables\(^{7}\) (corticospinal excitability and voluntary strength) predicting similar variance to the model. However, further analysis showed a nonsignificant weak correlation (r = .18, P = .492) between corticospinal excitability and voluntary strength, suggesting little association between the 2 predictor variables. Future research should address corticospinal excitability and its contribution to voluntary muscle strength.

The notion of increasing quadriceps strength after ACL-R is still controversial, as some have suggested that the presence of overpowering quadriceps force production may act to increase anterior translation of the tibia. A resultant anterior shear force at the knee joint may amplify the stress on the reconstructed ligament and increase the risk of a subsequent ACL rupture. Previous authors have reported that higher quadriceps-related moments during jump landing were predictive of a recurrent ACL rupture after an initial ACL-R.\(^{30}\) Increased quadriceps-to-hamstring strength ratio has not been found to predict anterior tibial shear.\(^{31}\) Others have suggested that decreased quadriceps function may alter functional movements such as gait and landing in a manner that decreases energy-absorption capabilities in the lower extremity.\(^{12}\) Some have theorized that long-term effects of quadriceps dysfunction after ACL-R may result in increased joint-surface breakdown, thus acting as a proposed mechanism for the increased risk of knee osteoarthritis after ACL-R.\(^{4}\) Therefore, quadriceps strength after ACL-R should be improved in a controlled manner that elicits general and coordinated strength gains of all muscles in the lower extremity, without creating strength imbalances that may provoke increased risk.

There are some limitations to consider from this investigation. The relatively small cohort of participants used in the current study represents a recreationally active population with a wide range of time elapsed post-ACL-R (54.4 ± 40.9 mo) and includes multiple graft types. The variability of the sample does not allow for conclusions based on a single surgical or rehabilitative technique; rather, this cohort may allow for a more generalizable interpretation of the overall ACL-R population. In addition, the outcome measures used in this study do not provide a comprehensive assessment of neuromuscular quadriceps function. We chose to assess isometric quadriceps strength, as it may be the mostly easily performed measurement in a variety of clinical settings. Future studies may consider evaluating the predictive capabilities of other modes of contraction (ie, isotonic, isokinetic) on predicting disability. Likewise, assessment of corticospinal excitability allowed for the easiest assessment of the most influential neural pathways involved in excitability of the quadriceps, yet future assessment of other measures of neural function may add to the predictive capabilities of the current model.

In conclusion, this specific predictive model indicates that voluntary quadriceps strength and corticospinal excitability are able to predict two-thirds of the variance in self-reported disability in patients with ACL-R. Quadriceps strength accounted for virtually all the predictive capability of the model. Clinically, interventions targeting quadriceps strength may be very beneficial in maintaining levels of self-reported function after ACL-R. Future research should focus on underlying factors contributing to voluntary strength, allowing prospective interventions to address the quadriceps dysfunction that persists in this population.

### References

8. Bryant AL, Kelly J, Hohmann E. Neuromuscular adaptations and correlates of knee functionality following...