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Electromyographic Predictors of Residual Quadriceps Muscle Weakness after Anterior Cruciate Ligament Reconstruction*

Malachy P. McHugh,† PhD, Timothy F. Tyler, MSPT, ATC, Michael G. Browne, MD, Gilbert W. Gleim, PhD, and Stephen J. Nicholas, MD

From the Nicholas Institute of Sports Medicine and Athletic Trauma, Lenox Hill Hospital, New York, New York

ABSTRACT

Background: Despite the high prevalence of residual quadriceps muscle weakness after anterior cruciate ligament reconstruction, specific predictive factors have not been identified.

Hypothesis: Electromyographic analysis is a better predictor of residual muscle weakness than is preoperative strength.

Study Design: Prospective cohort study.

Methods: The quadriceps muscle strength of 37 patients (25 men, 12 women) was measured before reconstruction and 5 weeks and 6 months after surgery. Quadriceps surface electromyographic signals were recorded during all of the strength tests. Integrated electromyographic analysis and median frequency measurements were computed as deficits on the involved side. Patients also performed a single-legged hop test at the 6-month follow-up examination.

Results: The patients had significantly lower strength, integrated electromyographic analysis, and median frequency measurements on the involved side at all three time intervals. The best predictor of the quadriceps muscle strength deficit at 6 months was the combination of the preoperative median frequency deficit and the 5-week postoperative strength deficit. The best predictor of the hop test deficit at 6 months was the combination of preoperative deficits in integrated electromyographic analysis and median frequency.

Conclusion: Preoperative electromyographic indices of quadriceps muscle function and early postoperative strength were predictive of residual weakness and impaired function 6 months after reconstruction.

The most common complications after ACL reconstruction include quadriceps muscle weakness, flexion contracture, and anterior knee pain.[11] Successful strategies have been developed to limit the incidence of flexion contractures and anterior knee pain. For example, it is well accepted that postoperative flexion contractures can be avoided by delaying surgery until the patient has regained full extension preoperatively.[1,7,9] A recent report from our institute demonstrated that full weightbearing immediately after ACL reconstruction dramatically reduces the incidence of anterior knee pain.[15] However, residual quadriceps muscle weakness remains a persistent problem after ACL reconstruction.

Preoperative quadriceps muscle strengthening has been advocated as a means of minimizing postoperative weakness,[13] but, surprisingly, preoperative isokinetic measurement of knee extension concentric strength has been shown to be a poor predictor of postoperative quadriceps muscle weakness.[7] Residual weakness may be primarily due to postoperative factors such as decreased weightbearing, knee joint effusion, pain, harvesting of the patellar tendon graft, and neuromuscular factors. Alternatively, isokinetic concentric strength measurements may not provide a sensitive indication of preoperative quadriceps muscle function. We examined whether surface EMG analysis could provide a useful adjunct to preoperative strength measurements. The purpose was to examine whether preoperative and early postoperative measures of quadriceps muscle strength, integrated EMG, and median frequency were predictive of residual quadriceps muscle weakness and impaired function 6 months after ACL reconstruction. We hypothesized that EMG analysis would be a better predictor of residual muscle weakness than would preoperative strength. The alternative hypothesis

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† Address correspondence and reprint requests to Malachy P. McHugh, PhD, Nicholas Institute of Sports Medicine and Athletic Trauma, Lenox Hill Hospital, 130 East 77th Street, New York, NY 10021.

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was that residual weakness was primarily due to postoperative factors and that indices of early postoperative quadriceps muscle function would be the best predictors of residual weakness.

MATERIALS AND METHODS

Quadriceps muscle strength of 37 patients (25 men, 12 women) was measured before ACL reconstruction and 5 weeks and 6 months after surgery. The study was approved by the institutional review board and all patients gave informed consent. The age of the patients was 31 ± 9 years (mean ± SD), the mean weight was 73 ± 12 kg, and the mean height was 172 ± 9 cm. Five weeks was chosen as the time for the early postoperative measurements because aggressive quadriceps muscle strengthening began then (see Appendix). Six months was chosen as the time for follow-up measurements because patients were permitted to return to full activities at that time. A sample of 37 patients was thought to be sufficient to examine clinically relevant associations between the variables of interest. With this sample size a correlation coefficient of at least 0.33 would be required to reach a significance level of $P < 0.05$.

An ipsilateral central one-third patellar tendon autograft (10 or 11 mm) was used for all reconstructions. The mean time from injury to surgery was 15 ± 36 months. The injury was categorized as acute (less than 2 months from injury to surgery) in 15 patients, as subacute (2 to 6 months from injury to surgery) in 7 patients, and as chronic (more than 6 months from injury to surgery) in 15 patients. Nine patients had a lateral meniscal tear, 10 had a medial meniscal tear, and 4 patients had both medial and lateral meniscal tears. Two patients had grade II medial collateral ligament sprains, and one patient had a grade III lateral collateral ligament sprain. Postoperatively, patients were permitted weightbearing as tolerated, with formal rehabilitation beginning at 1 week. Patients walked in a drop-lock knee brace for 4 weeks; the brace was locked for the first 2 weeks. The rehabilitation protocol involved passive resistance exercises of the hip during the 1st week, quadriceps muscle isometrics at week 1, isotonic leg press at week 2, StairMaster (StairMaster Health and Fitness Products, Inc., Kirkland, Washington) at week 4, isokinetic knee extension at week 6, jogging at 3 months, high-speed low-friction lateral movement at 4 months (slide board), cutting and jumping at 4 to 5 months, and, ideally, return to sport at 6 months (see Appendix).

Strength tests were performed isometrically on a dynamometer (Biodex System 2, Biodex Medical Systems, Inc., Shirley, New York) at 30° of knee flexion. At this angle, patellofemoral compression was minimized and the potential for pain during testing was limited. After a warm-up, three maximum contractions were performed on both the involved and noninvolved sides. Surface EMG signals were recorded for the rectus femoris, vastus lateralis, and vastus medialis muscles during all of the strength tests. The skin was shaved, cleaned, and abraded before the application of 10-mm diameter silver/silver-chloride electrodes on a 34 by 22 mm adhesive gel surface. All electrodes were placed 3 cm apart (center to center). The rectus femoris electrodes were placed midway along a line between the anterior superior iliac spine and the superior pole of the patella. The vastus lateralis electrodes were placed four finger-breadths proximal to the superolateral border of the patella along the assumed line of the muscle fibers. The vastus medialis electrodes were placed two finger-breadths proximal to the superomedial border of the patella along the assumed line of the muscle fibers. A ground electrode was placed on the patella.

The telemetered EMG signal was band-pass filtered from 10 to 500 Hz and sampled at 1000 Hz with a common-mode rejection ratio of 135 dB (Telemyo, Noraxon USA, Inc., Scottsdale, Arizona). The raw signal was full-wave rectified and integrated for analysis. Fast Fourier Transforms of 4096 points were applied to the raw signal from which median frequency was computed. All computations were performed using the software supplied by the manufacturer (Noraxon USA, Inc.).

In addition to strength measurements, goniometric measurements of knee extension were made at each time interval. The patients also performed a single-legged hop test at the 6-month follow-up examination. After warm-up, the peak distance of three hops was recorded for the involved and noninvolved sides. Subjective assessment of anterior knee pain was also recorded 6 months postoperatively. The patients reported their symptoms during activities of daily living, prolonged sitting, squatting, and during stair-climbing, and the results were used to categorize them into normal and anterior knee pain groups.[15]

Statistical Analysis

Repeated-measures analysis of variance was used to examine the effects of side (involved, noninvolved) and time (preoperative, 5 weeks postoperative, and 6 months postoperative) on strength, integrated EMG analysis, and median frequency results. Planned pairwise comparisons with Bonferroni corrections ($P = 0.05/3 = 0.017$) were made between the involved and noninvolved sides at each of the three time intervals. Deficits in strength, integrated EMG analysis, median frequency, and single-legged hop test results were computed to compare the degree of impairment between patients: ([noninvolved−involved]/noninvolved) × 100. Residual weakness was defined as a postoperative strength deficit of more than 20% at 6 months. Normal strength was defined as a deficit of less than 10%, and equivocal weakness was defined as a deficit of 10% to 20%.

Pearson product-moment correlations were used to identify which preoperative and 5-week postoperative deficits were associated with quadriceps muscle strength deficit at 6 months. Variables with significant correlations ($P < 0.05$) were entered into a stepwise multiple regression to determine the best predictors of strength deficit at 6 months. A limit of three variables was entered to have more than 10 patients per predictive variable. Variables were tested for normality of distribution before entry into multiple regression. Predictors of a single-legged hop test deficit at 6 months were tested similarly.

RESULTS

Patients had significantly lower strength, integrated EMG, and median frequency results on the involved side at all three time intervals (Fig. 1). These differences were most apparent 5 weeks after surgery (side × time, $P <$ 0.001). The average strength deficit at 6 months was 13% ± 17%. Fourteen patients had residual quadriceps muscle weakness at 6 months, with 9 categorized as equivocal and 14 as normal. Strength deficit at 6 months was correlated with preoperative deficits in strength ($r = 0.4$, $P < 0.01$), integrated EMG analysis results ($r = 0.34$, $P < 0.05$), and median frequency ($r = 0.54$, $P < 0.001$) and with 5-week postoperative deficits in strength ($r = 0.54$, $P < 0.01$), integrated EMG analysis results ($r = 0.36$, $P < 0.05$), and median frequency results ($r = 0.35$, $P < 0.05$). On the basis of Kolmogorov-Smirnov Z tests, all computed deficits were normally distributed. Preoperative deficits in median frequency and strength and a 5-week postoperative deficit in strength were entered into a stepwise multiple regression. On the basis of multiple regression analysis, the combination of preoperative median frequency deficit and 5-week postoperative strength deficit was the best predictor of quadriceps muscle strength deficit at 6 months ($r^2 = 0.45$, $P < 0.001$). The regression equation was

$$y = 0.55(\pm1.1)x_1 + 0.32(\pm0.63)x_2 - 0.04(\pm0.3)$$

where y = strength deficit at 6 months (20% = 0.2), x_1 = preoperative median frequency deficit, and x_2 = 5-week postoperative strength deficit.

The single-legged hop test deficit at 6 months was 23% ± 19%. Patients with residual weakness had a hop test deficit of 39% ± 19%, compared with 20% ± 9% in the patients with equivocal weakness and 13% ± 17% in patients with normal strength (group effect, $P < 0.001$; residual weakness group higher than normal group, $P < 0.01$). Hop test deficit at 6 months was correlated with preoperative deficits in strength ($r = 0.38$, $P < 0.05$), integrated EMG analysis results ($r = 0.56$, $P < 0.001$), and median frequency ($r = 0.35$, $P < 0.05$). None of the 5-week postoperative deficits were correlated with a hop test deficit at 6 months. The best predictor of a hop test deficit at 6 months was the combination of preoperative deficits in integrated EMG analysis and median frequency results ($r^2 = 0.4$, $P < 0.001$). The full regression equation was

$$y = 0.37(\pm0.58)x_1 + 0.44(\pm1.3)x_2 + 0.142(\pm0.2)$$

where y = hop test deficit (20% = 0.2), x_1 = preoperative integrated EMG analysis deficit, and x_2 = preoperative median frequency deficit.

The strength deficit at 6 months was unaffected by chronicity of injury ($P = 0.21$) or pathologic condition of the meniscus (0.69). However, given the respective sample sizes, there was limited statistical power to detect significant effects of chronicity or of a pathologic condition of the meniscus. At an alpha level of 0.05 or less, there was 80% power to detect an 18% difference in strength deficit between the patients with chronic versus acute injuries. The observed difference was 11% ($P = 0.21$). Similarly, there was 80% power to detect a 17% difference between patients with a pathologic condition of the meniscus compared with patients with normal menisci. The observed difference was less than 4% ($P = 0.69$).

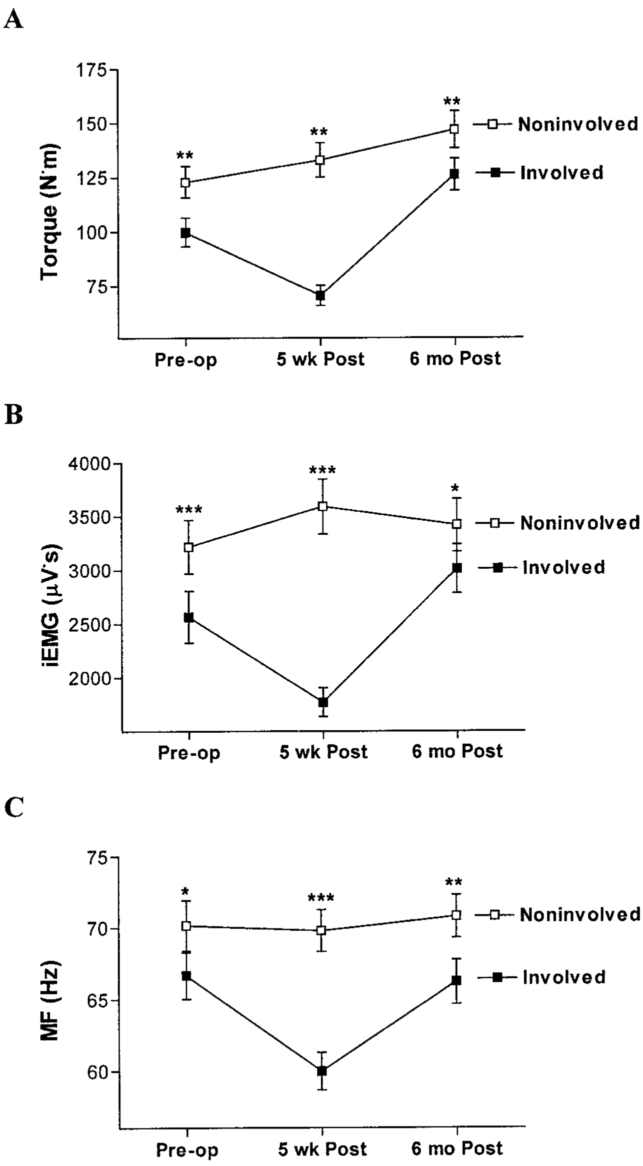

Figure 1. Knee extension torque in Newton-meters (A), integrated EMG analysis (iEMG) in microvolt seconds (B), and median frequency (MF) in hertz (Hz) (C) were lower on the involved side than on the noninvolved side (***, $P < 0.001$; **, $P < 0.01$; and *, $P < 0.05$). The differences between the involved and the noninvolved sides were most apparent 5 weeks after ACL reconstruction (side × time, $P < 0.001$ in B and C). Pre-op, preoperative; 5 wk Post, 5 weeks postoperative; 6 mo Post, 6 months postoperative.

Five patients lacked 5° or more extension 6 months after surgery, and all but one of these patients lacked full extension (equal to the contralateral limb) before surgery. Six patients had anterior knee pain at 6 months. These patients had greater strength deficits before surgery than did those without anterior knee pain (33% ± 16% compared with 13% ± 20%, $P < 0.05$) and at 5 weeks after surgery (68% ± 21% compared with 40% ± 19%, $P < 0.01$). No patients reported pain during strength tests at any of the time intervals.

DISCUSSION

The results demonstrated that residual weakness was related to both preoperative and postoperative factors. The best predictors of residual weakness were the preoperative deficit in EMG median frequency and early postoperative quadriceps muscle weakness. Forty-five percent of the variability in quadriceps muscle strength deficit 6 months after surgery was explained by a combination of preoperative median frequency deficit (35%) and early postoperative strength deficit (10%). The quadriceps muscle strength test was used to provide an isolated measure of quadriceps muscle function. To complement this test, a single-legged hop test was used to provide a measure of functional performance. Preoperative EMG analysis provided the best predictor of functional performance 6 months after surgery. Forty percent of the variability in hop-test deficit at 6 months was explained by a combination of preoperative integrated EMG deficit (31%) and preoperative median frequency deficit (9%).

Measurement of isometric strength at 30° of knee flexion is not typically used in this patient population. It was used here to get a valid assessment of early postoperative strength without inducing pain. However, concentric or eccentric isokinetic testing may have provided better measurements of quadriceps muscle strength. Despite this potential limitation, it was clear that although some patients recovered normal strength by 6 months, others still had marked weakness. This finding is in agreement with findings of earlier studies that demonstrated a high prevalence of residual quadriceps muscle weakness after ACL reconstruction.[7,11] The single-legged hop test has been used to demonstrate the association between weakness and functional performance.[11] This association was also apparent among our patients, with significantly greater hop-test deficits in those with residual weakness.

The EMG analysis demonstrated marked impairments in quadriceps muscle function before and after ACL reconstruction. The deficits in integrated EMG analysis and median frequency presumably reflected a combination of quadriceps muscle inhibition and atrophy. In an earlier report, we attributed decreased integrated EMG analysis at 1 day and at 3 weeks after ACL reconstruction to quadriceps muscle inhibition because the effect at 1 day was before the development of significant atrophy.[15] Similarly, an increase of integrated EMG analysis results with strength training has been attributed to increased motor unit activation.[4,12] However, in the present study it was not possible to determine whether the integrated EMG analysis deficits reflected inhibition or a combination of inhibition and atrophy.

Two studies have previously examined the frequency content of the EMG signal in ACL-deficient patients.[8,14] Tho et al.[14] examined the quadriceps and hamstring muscle EMG fatigue responses in ACL-deficient patients but did not address actual deficits on the involved side in the unfatigued state. McNair and Wood[8] demonstrated lower vastus lateralis muscle median frequency on the involved side in ACL-deficient patients. Lower median frequency was attributed to selective atrophy of fast-twitch fibers. This assumption was based on the fact that median frequency primarily reflects muscle fiber conduction velocity and that conduction velocity is higher in fast than in slow muscle fibers.[2,5,6] However, conduction velocity and median frequency are also sensitive to changes in muscle fiber diameter independent of fiber type, such as occurs with shortening or lengthening of a muscle.[10] Therefore, it is more likely that lower median frequency reflected nonselective atrophy of all fibers. Future research should address the potential for using median frequency as an indicator of muscle fiber atrophy.

Despite the fact that preoperative EMG measures and early postoperative strength measures had some predictive value, more than 50% of the variability in strength and hop-test deficits 6 months after surgery remained unexplained. A range of factors can affect quadriceps muscle function after ACL reconstruction, including decreased weightbearing, knee joint effusion, pain, harvesting of the patellar tendon graft, and neuromuscular factors. Additionally, factors such as chronicity of injury and pathologic conditions of the meniscus may also be important. The limited sample size and study design used here precluded analysis of the potential effects of all of these additional factors.

A statistical association between preoperative EMG measurements and postoperative quadriceps muscle function is of limited clinical value if patients at risk cannot be successfully identified. Ten of 13 patients with a preoperative median frequency deficit of 10% or more had residual weakness 6 months after surgery, compared with only 3 of 24 patients with a preoperative median frequency deficit of less than 10%. Therefore, the relative risk of developing residual quadriceps muscle weakness based on a preoperative median frequency deficit was 6:1. Future research should prospectively test this finding in a larger sample of patients.

Clinically, the ultimate goal is to prevent patients from developing residual quadriceps muscle weakness. Although our results and those of a previous study[7] indicate that preoperative strength is not a good predictor of residual weakness, there may still be a role for preoperative strengthening exercises. High-intensity eccentric quadriceps muscle contractions may be beneficial because eccentric contractions provide the greatest hypertrophic stimulus in atrophied muscle[3] and induce a marked neural training effect.[4] Additionally, in the early postoperative period, when high-intensity quadriceps muscle contractions are not possible, eccentric training of the uninvolved quadriceps muscle may be beneficial. The carryover of strength gains in a trained limb to the contralateral limb (cross education) is most effective with eccentric training.[4]

In summary, patients had significant deficits in strength, integrated EMG analysis, and median frequency results before ACL reconstruction, 5 weeks after surgery, and 6 months after surgery. These deficits were most profound in the early postoperative period. Preoperative EMG indices of quadriceps muscle function were predictive of residual weakness and impaired functional performance, whereas preoperative strength had little predictive value.

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APPENDIX

Nicholas Institute of Sports Medicine and Athletic Trauma Rehabilitation Guidelines for Arthroscopically Assisted ACL Reconstruction

Day 1 to week 1

- Continuous passive motion 2 hours twice per day; increase range of motion as tolerated. Discontinue when 0° to 110° achieved.
- Ice as indicated; no more than 15 minutes each hour.
- Weightbearing as tolerated with crutches. Discontinue crutches if able to stand on involved leg with brace locked.
- Drop lock knee brace in locked position except when exercising. Remove brace for therapeutic exercises and continuous passive motion.
- Passive range of motion per patient tolerance; 0° to 135°.
- Supine and prone sustained extension stretching—**Never put anything under the knee.**
- Supine wall slide.
- Seated hamstrings (carpet drags) / prone hamstring curls / sports cord knee flexion.
- Stationary bicycle.
- Isometric quadriceps muscle contraction in complete/supported extension: biofeedback/electrical stimulation.
- Straight leg raises in 4 directions *without* extension lag, resistance above the knee. If lag, patient may perform straight leg raises with brace locked.
- Isometric quadriceps muscle contractions at 0° and 90° with/without electric stimulation.
- Patella mobilizations.
- Modalities to decrease swelling and pain.
- Flexibility exercises: hamstring, quadriceps, gastrocnemius/soleus, iliotibial band, and hip flexors.
- Upper and lower body cycling aerobic program; upper body and midbody strengthening program.

Week 2

- Continue with the above program.
- Balance exercises with partial weightbearing.
- Bilateral “minisquats” (0° to 40°); progress to semisquats.
- Bilateral leg press.
- Toe and heel raises.
- Unlock brace for sitting (monitor for loss of extension). Continue with locked brace for sleeping.
- Unlock brace for ambulation if straight leg raise without lag.

Week 3

- Discontinue brace at night if extension is maintained.
- Walking on heels.

- Standing balance and proprioception exercises with full weightbearing (provided adequate quadriceps muscle control).

Week 4

- Discontinue brace for ambulation. Monitor for loss of extension.
- Short arc quadriceps exercises.
- Wall sits.
- Unilateral eccentric leg press.
- StairMaster as tolerated.
- Lateral shuffles.
- Double leg hops.

Week 6

- Full arc quadriceps muscle exercises/Isokinetic program - progress as tolerated (monitor for patellofemoral pain).
- BAPS and Anklizer full weightbearing.
- Bilateral “semisquats” (0° to 80°).
- Cariocas.
- Aqua jogger program with wet vest.

Week 8

- Single-legged hops.
- Assess hip strength with manual maximum test.
- Unilateral “minisquats” (0° to 40°); Progress to semisquats.

Weeks 12 to 16

- Sliding board and lateral sliding exercises.
- Rollerblading and ice skating as tolerated. (Check with physician, may need ACL orthosis).
- Plyometrics program.
- Jogging straight ahead.
- Jumping rope.
- Lunges sideways/forward.

Week 20

- Cutting/agility drills and sport-specific training.

Week 24

- Advance to full sports activities if less than 20% strength deficit. Brace if arthrometer testing shows more than 5 mm side-to-side difference or less than 3 mm improvement from preoperative.