An Electromyographic Investigation of 4 Elastic-Tubing Closed Kinetic Chain Exercises After Anterior Cruciate Ligament Reconstruction

Shane S. Schulthies, PhD, PT, ATC*; Mark D. Ricard, PhD; Kimbie J. Alexander, MS; J. William Myrer, PhD

Brigham Young University, Provo UT 84602

**Objective:** To determine the electromyographic (EMG) activity of the vastus medialis oblique (VMO), vastus lateralis (VL), semitendinosus and semimembranosus (ST), and biceps femoris (BF) muscles during 4 elastic-tubing closed kinetic chain exercises in postoperative patients with anterior cruciate ligament (ACL)-reconstructed knees.

**Design and Setting:** A 4 × 4 repeated-measures analysis of variance design guided this study. Independent variables were type of exercise and muscle; the dependent variable was EMG activity.

**Subjects:** Fifteen patients, 5 to 24 weeks after ACL reconstruction.

**Measurements:** Subjects performed 4 exercises (front pull, back pull, crossover, reverse crossover) with elastic tubing attached to the foot of the uninjured leg. Time- and amplitude-normalized EMG activity was recorded from the VMO, VL, ST, and BF muscles of the injured leg. The hamstrings:quadriceps ratio was calculated.

**Results:** The normalized VMO, VL, and BF EMG activity ranged from 25% to 50% of maximum voluntary isometric contraction for the 4 exercises. The ST ranged from 12% on the back pull to 58% on the front pull. The hamstrings:quadriceps ratios were 137% (front pull), 115% (crossover), 70% (back pull), and 60% (reverse crossover).

**Conclusions:** We suggest that clinicians use these exercises during early ACL rehabilitation since they incorporate early weightbearing with hamstring and quadriceps coactivation.

**Key Words:** EMG, ACL rehabilitation, knee rehabilitation

A major objective for patients in rehabilitation after anterior cruciate ligament (ACL) reconstruction is to strengthen the quadriceps without excessively stressing the ACL graft. Isolated knee-extension exercises performed during the last 60° produce significant strain on the ACL graft.1 Hamstrings contractions pull the tibia posteriorly, reducing the magnitude of the anterior shear force produced by the quadriceps.2-4 Exercises involving a cocontraction of the hamstrings have been suggested to strengthen the quadriceps in the last 60° of knee extension without stressing the ACL graft.5-9

During closed kinetic chain exercises, the distal segment of a joint meets with a force that restrains or prohibits its free motion.10 These exercises increase joint compression, which enhances joint stability and protects the graft.3,5,8,9,11 Several authors have also suggested that closed kinetic chain exercises produce a cocontraction of the hamstring muscles, which reduces the anterior shear force at the tibiofemoral joint when compared with open chain knee extension exercises.3,5,8,9 However, the muscle activity of specific closed kinetic chain exercises has not been thoroughly researched.

The hamstrings appear to be minimally active, ranging from 1% to 10% maximum voluntary isometric contraction (MVIC) during stair stepping.12,13 and quarter squats.3,14 Hamstrings: quadriceps electromyographic (EMG) ratios have been computed for other commonly prescribed closed kinetic chain exercises and range from 61% to 74%.3 These findings have led researchers to question the effectiveness of closed chain exercises in controlling anterior shear forces at the knee.3,14

Elastic tubing has been suggested as an effective tool for performing closed kinetic chain exercises.1 Gray advocated attaching the elastic tubing to the uninjured leg, thus causing resistance through the pelvis to the injured leg. We feel this technique provides resistance to the closed chain leg and can be used to emphasize different muscles, depending on the direction of pull of the elastic tubing in relation to the patient’s body.16 Hamstrings:quadriceps ratios up to 156% have been recorded using this technique, suggesting a strong cocontraction of the hamstrings.16

All the studies cited used healthy individuals as research subjects. Therefore, the purpose of our study was to describe and compare the EMG activity of the vastus medialis oblique (VMO), vastus lateralis (VL), semitendinosus and semimembranosus (ST), and biceps femoris (BF) muscles during 4
elastic-tubing closed kinetic chain exercises in patients 5 to 24 weeks after ACL reconstruction.

METHODS

A 4 × 4 factorial repeated-measures design guided this study. Normalized EMG activity was the dependent variable. The 2 independent variables were muscle group (VMO, VL, ST, and BF) and exercise (front pull, back pull, crossover, and reverse crossover). Subjects performed all exercises in a single session, with the order of the exercises counterbalanced.

Subjects

Eight males and 7 females (age = 27.4 ± 9.1 years, wt = 71.2 ± 14.2 kg) who were 12.5 ± 5.7 weeks postoperative ACL reconstruction surgery (9 with patellar tendon autografts and 6 with semitendinosus autografts) volunteered for this study. All subjects signed a university-approved informed consent form. The study was approved by the Committee on Human Research at Brigham Young University.

Instrumentation

The start and end of each closed kinetic chain exercise movement was identified using an Advanced Mechanical Technology Incorporated force plate (Newton, MA). Tension in the elastic tubing was recorded using an Omega Engineering LCK-250 force transducer (Stamford, CT). Positions of the support knee and hip were monitored using Penny & Giles goniometers (Santa Monica, CA). EMG signals were collected with Motion Control preamplifier surface electrodes (Salt Lake City, UT), containing 3 silver-silver chloride discs 12 mm in diameter and a 3-mm interelectrode space. These electrodes have a preamplified gain of 375 at 300 Hz, a bandwidth of 8 to 26 KHz, a common mode rejection ratio of 100 dB at 60 Hz, and input impedance of 100,000 megaohms. Vertical force, EMG, goniometer, and force transducer data were recorded using an AST 486 computer interfaced to the respective amplifiers by an Ariel 16-channel, 12-bit analog to digital converter (La Jolla, CA). Resistance during the MVIC was provided using a Cybex Fitness System leg extension machine (Ronkonkoma, NY), with the resistance arm locked at 50° knee flexion and the resistance level superior to the malleoli. Resistance during the closed kinetic chain exercises was provided using elastic tubing with an internal diameter of 4.8 mm, an outside diameter of 11.1 mm, and a length of 1.83 m; a padded foot strap served to attach the elastic cord to the leg (Functional PT Products, Heber City, UT).

Description of the Exercises

The following procedure was used in each of the 4 exercises. One end of the elastic tubing was attached to the uninjured leg at the level of the malleoli; the other end was attached to the fixed force transducer. The patient stepped away from the

Figure 1. The front-pull exercise at starting and ending positions (A) and at midmovement (B). The subject stands on the injured leg, with the uninjured leg positioned behind the injured leg. While balancing on the injured leg, the subject flexes the uninjured leg at the hip and knee, pulling the tubing forward (B). The subject then slowly returns to the ending position (A).
tubing attachment site, stretching the tubing to obtain a resistance to 20% of body weight. The subject crouched so that the hips and knees were flexed to approximately 50°, with most of the body weight on the injured leg (Figures 1–4).

**Front pulls.** Subjects faced away from the fixed attachment of the elastic tubing so that the tubing pulled them backward. The subject stood on the injured leg, with the uninjured leg positioned behind the injured leg, and the hip and knee extended (Figure 1A). While balancing on the injured leg, the subject flexed the uninjured leg at the hip and knee, pulling the tubing forward (Figure 1B). The subject then slowly returned to the starting position (Figure 1A).

**Back pulls.** Subjects faced the fixed attachment of the elastic tubing so that the tubing pulled them forward. The subject stood on the injured leg, with the uninjured leg flexed at the hip and knee (Figure 2A). While balancing on the injured leg, the subject extended the uninjured leg at the hip and knee, pulling the tubing backward (Figure 2B). The subject then slowly returned to the starting position (Figure 2A).

**Crossovers.** Subjects stood at a 90° angle to the fixed end of the tubing so that the uninjured extremity was closest to the tubing attachment, with the feet slightly wider apart than shoulder width (Figure 3A). Subjects adducted the hips, crossing the uninjured leg in front of the injured leg (Figure 3B), and returned slowly to the starting position (Figure 3A).

**Reverse crossovers.** Subjects stood at a 90° angle to the fixed end of the tubing so that the injured extremity was closest to the tubing attachment, with the hips adducted and the legs crossed so that the foot of the uninjured leg was in front of the foot of the injured leg (Figure 4A). Subjects abducted the hips until the feet were slightly wider apart than shoulder width (Figure 4B) and returned slowly to the starting position (Figure 4A).

**Procedures**

An orientation session preceded the testing session by 2 days. During orientation, subjects practiced the exercises until they could maintain balance on the affected extremity and execute each exercise through the required range of motion (between 35° and 60° of flexion for both the hip and knee) in a smooth fashion, as subjectively determined by the investigator. During the testing session, surface electrodes were placed overlying the VMO, VL, ST, and BF muscles of the injured leg, with the electrodes aligned parallel to the muscle fibers. We attached the VMO electrode superomedial to the patella over the most prominent portion of the contracted muscle. The VL electrode placement was at one half the distance between the superior pole of the patella and the anterior superior iliac spine on the lateral aspect of the thigh. We positioned the biceps femoris electrode at a superolateral point one third of the distance between the ischial tuberosity and the lateral joint line. The ST electrode was positioned at a superomedial point one third of the distance between the ischial tuberosity and the medial joint line. Each subject completed 3 1-second MVICs of the quadriceps and hamstrings. The contraction with the largest average amplitude was used to normalize the EMG signals collected during the exercise. The maximum contrac-

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**Figure 2.** The back-pull exercise at starting and ending positions (A) and at midmovement (B). The subject stands on the injured leg, with the uninjured leg flexed at the hip and knee (A). While balancing on the injured leg, the subject extends the uninjured leg at the hip and knee, pulling the tubing backward (B). The subject then slowly returns to the ending position (A).
Figure 3. The crossover exercise at starting and ending positions (A) and at midmovement (B). The subject stands at a 90° angle to the fixed end of the tubing so that the uninjured extremity is closest to the tubing attachment, with the feet slightly wider apart than shoulder width (A). The subject adducts the hips, crossing the uninjured leg in front of the injured leg (B), and slowly returns to the ending position (A).

Figure 4. The reverse-crossover exercise at starting and ending positions (A) and at midmovement (B). The subject stands at a 90° angle to the fixed end of the tubing, so that the injured extremity is closest to the tubing attachment, with the hips adducted and the legs crossed so that the foot of the uninjured leg is in front of the foot of the injured leg (A). The subject abducts the hips until the feet are slightly wider apart than shoulder width (B) and slowly returns to the ending position (A).

Actions were performed with the subjects in a sitting position, with the hip at 90° and the knee at 50° of flexion, as measured with a goniometer. A 3-minute rest period was given between the MVICs and the experimental trials to prevent fatigue.

The elastic tubing resistance level was recorded throughout the movement. Since elastic tubing resistance is variable, the exercises were set up so that a resistance of 20% of the subject’s body weight was achieved midway through the
movement. The EMG, goniometer, tension in elastic cord, and force plate signals were collected for 3 seconds for each trial, at 1000 Hz, with a 1-minute rest between exercises. Five trials were collected for each exercise, and the order of exercises was counterbalanced. The subjects tapped the foot of the uninjured leg on a force plate at the beginning and the end of each contraction to allow collection of data from 1 repetition.

**Analysis of Data**

We recorded 5 trials for each exercise and used the vertical force signal, shown in Figure 5, to identify the start and end of each trial. The raw EMG signals were then bandpass filtered 20 to 500 Hz, full-wave rectified, and low-pass filtered at 6.0 Hz to produce a linear envelope. We time normalized the EMG data, using a cubic spline routine, to the mean time required to perform 1 repetition (1.65 ± 3.08 seconds). Since the isometric data were collected for 1 second and the exercise data were collected for 1.65 ± 3.08 seconds, we needed to account for the differences in time. We, therefore, multiplied the area collected during the exercise by 0.606 (1/1.65) and then divided the exercise data by the MVIC data to amplitude normalize each muscle at each trial. We then averaged the EMG data of the 5 trials for each muscle and recorded the result as the dependent variable. We calculated the hamstrings: quadriceps ratio by combining the average of the 5 EMG

![Figure 5. Typical trial for a front-pull exercise showing ground reaction force, elastic tubing force, and raw EMG for VMO, VL, ST, and BF muscles. The subject taps the foot of the uninjured leg on the force plate at the start and end of each trial. The solid vertical lines indicate the start and end of each trial, which are identified from the force plate data. Only the data between the solid vertical lines were retained for analysis in our study.](image-url)
signals of the BF and the ST (hamstrings), then dividing by the combined average of the 5 EMG signals of the VMO and the VL (quadriceps).

A 1-factor analysis of variance (ANOVA) was performed to test the effect of surgical technique. Because no effect was found, the data were pooled, and statistics were performed on these pooled data. A $4 \times 4$ repeated-measures ANOVA was performed to determine differences between the muscles (VMO, VL, ST, and BF) and the exercises (front pull, back pull, crossover, and reverse crossover). A single-factor repeated-measures ANOVA was used to determine differences in the hamstrings:quadriceps ratio between exercises. Tukey post hoc tests were used to test for significant differences between groups. Significance for all comparisons was set at $P = .05$.

RESULTS

The EMG values for each muscle recorded during the 4 closed kinetic chain exercises are found in Table 1. Results of the main-effects test on muscle showed no difference between muscles ($F_{3,42} = 0.45, P = .72$). Results of the main-effects test on exercise indicated significant differences between exercises ($F_{3,42} = 34.69, P = .001$). The results indicated a muscle-by-exercise interaction ($F_{9,126} = 19.28, P = .001$). We were primarily interested in the muscle differences, so only muscle-within-exercise post hoc comparisons are listed in Table 1. The hamstrings:quadriceps ratios recorded during the 4 closed kinetic chain exercises are found in Table 2. Results of the exercise main-effects test indicated a significant difference in the hamstrings:quadriceps ratio ($F_{3,42} = 28.16, P = .001$).

DISCUSSION

Subjects tolerated the exercises well, and no subject reported symptoms either during or after the exercises. In fact, these exercises are commonly used in our rehabilitation protocols as soon as full weightbearing is achieved.

Many authors have suggested that closed kinetic chain exercises be part of ACL rehabilitation.\textsuperscript{18–20} Shelborne and Nitz\textsuperscript{20} recommended closed kinetic chain exercises as soon as unassisted weightbearing of the involved extremity is possible. They emphasized the need for immediate weightbearing before exposure to dangerous joint loads for the sake of the patient’s tolerance, normal proprioceptive and functional patterns in musculature, and coordination.\textsuperscript{20} Mangine and Noyes\textsuperscript{19} suggested that early weightbearing is important in rehabilitation after ACL reconstruction. They recommended that balance, hamstring strength training, and control of joint forces during weightbearing be emphasized.\textsuperscript{19} Malone and Garrett\textsuperscript{18} suggested that middle range-of-motion weightbearing activities are better tolerated and are safer than their open chain counterparts. We feel that these 4 elastic-tubing exercises accomplish these goals of early weightbearing using middle range of motion, controlling the joint forces by activating the hamstrings, and stressing balance, coordination, and proprioception.

We hypothesized that resistance during the front-pull exercise tends to cause hip flexion, hip external rotation, knee extension, and knee external rotation of the injured leg. Muscular resistance to these motions should activate the hamstrings more than the quadriceps, and the medial hamstrings more than the lateral hamstrings.\textsuperscript{16} Our results support this hypothesis in that the ST and BF were more active than both the quadriceps (Table 1). This hamstrings contraction generates a posterior shear force on the tibia, which decreases ACL stress.\textsuperscript{15} Our results suggest that patients can activate the quadriceps with a cocontraction of the hamstrings during the front-pull exercise early in rehabilitation, with reduced risk of stressing the ACL graft.

We hypothesized that resistance during the back-pull exercise tends to cause hip extension, hip internal rotation, knee flexion, and internal rotation of the injured leg. This should activate the quadriceps more than the hamstrings and the lateral hamstrings more than the medial hamstrings.\textsuperscript{16} Our results

<table>
<thead>
<tr>
<th>Exercises</th>
<th>Hamstrings:Quadriceps Ratios (%)</th>
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</thead>
<tbody>
<tr>
<td>Front pull</td>
<td>137 ± 62\textsuperscript{a}</td>
</tr>
<tr>
<td>Back pull</td>
<td>70 ± 44</td>
</tr>
<tr>
<td>Crossover</td>
<td>115 ± 44\textsuperscript{b}</td>
</tr>
<tr>
<td>Reverse crossover</td>
<td>60 ± 21</td>
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</tbody>
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\textsuperscript{a} Significantly greater than all other conditions. 
\textsuperscript{b} Significantly greater than back pull and reverse crossover.

Table 2. Normalized Mean EMG Values of the Hamstrings:Quadriceps Ratios for 4 Elastic-Tubing Closed Kinetic Chain Exercises

<table>
<thead>
<tr>
<th>Exercises</th>
<th>VMO (%)</th>
<th>VL (%)</th>
<th>ST (%)</th>
<th>BF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front pull</td>
<td>42.33 ± 17.4</td>
<td>35.70 ± 10.3</td>
<td>57.63 ± 25.3\textsuperscript{a}</td>
<td>49.38 ± 20.2\textsuperscript{b}</td>
</tr>
<tr>
<td>Back pull</td>
<td>37.10 ± 14.5\textsuperscript{c}</td>
<td>38.21 ± 10.8\textsuperscript{d}</td>
<td>12.82 ± 5.4</td>
<td>39.99 ± 14.2\textsuperscript{c}</td>
</tr>
<tr>
<td>Crossover</td>
<td>31.43 ± 11.2</td>
<td>27.18 ± 8.3</td>
<td>39.96 ± 21.4\textsuperscript{e}</td>
<td>27.34 ± 12.2</td>
</tr>
<tr>
<td>Reverse crossover</td>
<td>32.56 ± 12.37\textsuperscript{e}</td>
<td>35.38 ± 12.5\textsuperscript{f}</td>
<td>15.89 ± 9.8</td>
<td>25.11 ± 10.6\textsuperscript{c}</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Significantly greater than VMO and VL. 
\textsuperscript{b} Significantly greater than VL. 
\textsuperscript{c} Significantly greater than VL. 
\textsuperscript{d} Significantly greater than ST. 
\textsuperscript{e} Significantly greater than VL and BF.
support this hypothesis, showing the VMO, VL, and BF muscles to be more active than the ST (Table 1). While hamstrings activity and the hamstrings:quadriceps ratio were less than for the front pull, hamstrings activity is comparable with that previously recorded during the quarter-squat exercise.3

We hypothesized that resistance during the crossover exercise tends to cause hip abduction, hip external rotation, knee flexion, and external rotation of the injured leg. This should activate the hamstrings more than the quadriceps and the medial hamstrings more than the lateral hamstrings. Our results support this hypothesis, showing that the ST was significantly more active than the VL or the BF (Table 1). The hamstrings:quadriceps ratio was significantly higher in the crossover exercise than in the back-pull and reverse-crossover exercises, second only to the front-pull exercise.

We hypothesized that resistance during reverse-crossover exercise tends to cause hip adduction, hip internal rotation, knee flexion, and internal rotation of the injured leg. This should activate the quadriceps more than the hamstrings, and the lateral hamstrings more than the medial hamstrings. Our results support this hypothesis, showing that the VMO, VL, and BF muscles were all more active than the ST, and the VL was more active than the BF (Table 1).

Closed kinetic chain exercises have been prescribed during rehabilitation because of the cocontraction of the hamstrings;21 however, many closed kinetic chain exercises produce a relatively low hamstrings:quadriceps ratio.2,4,7,8 Studies conducted on stair-stepping activities have resulted in hamstrings activity ranging from 4% to 15% of maximum contraction and hamstrings:quadriceps ratios from 10% to 30%.2,12,13 Brask et al2 suggested that the contraction of the hamstrings muscles may be insufficient to control anterior shear forces. Quarter squats have resulted in hamstring activity from 3% to 4%, with hamstrings:quadriceps ratios of approximately 4%.14 Graham et al3 studied 5 closed kinetic chain exercises, including unilateral one-quarter squats, leg extensions, lateral step-ups, and movements on the Fitter (Fitter International, Inc, Calgary, AB, Canada), Stair Master 4000 (Stair Master Sports/Medical Products, Inc, Kirkland, WA), and slide board.3 Mean hamstrings:quadriceps ratios ranged from 21.5% for the leg extension to 73.9% for the slide board. Graham et al3 suggested that the higher ratios will better reduce the anterior shear forces. The front-pull and crossover exercises have the greatest hamstrings:quadriceps ratios reported by any closed kinetic chain exercises in the current literature. Our study is the first to report the ratios using patients with ACL-reconstructed knees as subjects. The hamstrings:quadriceps ratios were 137% (front pull), 115% (crossover), 70% (back pull), and 60% (reverse crossover). Bachler et al16 reported ratios of 156% for the front pull and 83% for the crossover. While all 4 exercises produced hamstrings:quadriceps cocontraction, the front-pull and crossover exercises produced significantly higher hamstrings:quadriceps ratios. Theoretically, this may reduce the anterior shear force. We believe these exercises can be safely performed early in ACL rehabilitation.

Most of our exercises produced myoelectric activity in excess of 30% of MVIC, higher than that produced by squats, stair stepping, or step-ups (3.5% to 25%).2,3,12,14,16 While muscle length changes, contraction velocities, contraction type, and other factors have hindered a description of the precise EMG-tension relationship,21 exercises that produce high EMG activity should result in greater strength gains than exercises that produce low EMG activity.17,22 Therefore, performing our exercises may result in greater strength gains, especially in the hamstrings, than previously described closed kinetic chain exercises. However, due to differences in subjects, methods, instrumentation, contraction velocities, and range of motion, comparisons of myoelectric activity between studies is difficult. In order to test this hypothesis, patients should exercise using different closed kinetic chain exercises and be tested for differences in strength gains.

Patellofemoral pain has been reported as a common side effect after ACL reconstruction.20 Patellofemoral pain is also believed to be caused by increased VL activity when compared with VMO activity.24 The activity of the VMO when compared with the VL may, therefore, be of clinical interest. Bachler et al16 showed a significant difference between the activity of the VMO when compared with the VL for the front-pull and the crossover exercises.1 Our VMO-VL difference showed a trend similar to the results of Bachler et al,16 yet it was not significant at the P = .05 level. Since the number of patients with patellofemoral pain in our study was not recorded, direct conclusions about the treatment of patellofemoral pain with these exercises are not possible. We suggest that the activity of the VMO and VL during these exercises be recorded on patients with patellofemoral pain.

CONCLUSIONS

Based on our results, we recommend all 4 closed kinetic chain elastic-tubing exercises for ACL rehabilitation. The front-pull and crossover exercises have high hamstrings:quadriceps ratios that may reduce the anterior shear forces and are therefore indicated in early ACL rehabilitation.

REFERENCES


