Electromyographic Evaluation of Closed and Open Kinetic Chain Knee Rehabilitation Exercises

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Abstract: *The use of closed kinetic chain knee rehabilitation exercises has been advocated in recent years. The primary reason cited for employing closed kinetic chain exercises is that these exercises result in less anteroposterior (A/P) shear force at the knee joint, when compared with traditionally used open kinetic chain exercises. The purpose of this study was to determine the electromyographical (EMG) activity ratio of quadriceps to hamstrings occurring in the following exercises: unilateral one quarter squats, leg extensions (N-K Table), lateral step-ups, and movements on the Fitter (Fitter International, Inc), Stairmaster 4000 (Randal Sports/Medical Products, Inc), and slideboard. Ten female student-athletes participated in this study. EMG surface electrodes were applied over the rectus femoris and biceps femoris muscles. The subjects completed three maximum isometric contractions for both muscle groups to obtain baseline EMG data. They then performed repetitions of each exercise. These movements were videotaped simultaneously with a stationary shuttered video camera operating at 30 Hz. A computer program was used to analyze the videotaped performances for knee joint range of motion (ROM). Three trials of data were averaged. Baseline EMG activity was used to determine percentage of maximum EMG activity for each exercise. There were significant differences (p.<01) among the exercises for the following dependent variables: ROM, maximum angle, percent of maximum contraction, time of contraction, and total EMG (EMG area under the curve). This study suggests that the five closed kinetic chain exercises studied result in minimal A/P shear forces at the knee joint.*

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A major problem for the athletic trainer is selecting the appropriate exercise regimen for the anterior cruciate ligament (ACL) deficient knee. A properly designed exercise program should consider the disruptive potential of anteroposterior shear forces.[8] A/P shear forces result from increased quadriceps femoris muscle tension, which produces a potentially dangerous situation in which too much force can be directed through an injured or reconstructed ACL.[8-12,15,16,23,24]

Several authors[1,4,10,12,15,16,19,22-24] describe A/P shear force potential and warn against open kinetic chain exercises after ACL reconstruction. Therapeutic exercises designed to improve knee function should not generate large muscle forces that produce an imbalance of forces. Closed kinetic chain exercises reduce A/P shear force by increasing the joint compressive forces that occur when the extremity is loaded by body weight. Body weight provides inherent joint stability and allows for more strenuous strengthening workouts without the degree of shearing forces that occur with conventional open kinetic chain exercises.[20] Anterior shear forces of 0.20 times body weight in weight-bearing, and 0.43 times body weight in nonweight-bearing maximum isometric exercise have been reported.[15,21] Weight-bearing (closed kinetic chain) exercises cause less elongation of the ACL than nonweight-bearing (open kinetic chain) exercises.[9,17] Closed kinetic chain exercises have been found to be beneficial in ACL rehabilitation programs.[2,13,17,20]

Minimal research is available documenting the amount of muscle activity involved in commonly used closed kinetic chain knee rehabilitation exercises. The purpose of our study was to determine the electromyographical (EMG) activity ratio of quadriceps to hamstrings occurring in the following commonly used knee rehabilitation exercises: unilateral one quarter squats, leg extensions (N-K table), lateral step-ups, and movements on the Fitter, slideboard, and Stairmaster 4000.

Methods

Ten female student-athletes (age=21.0±1.3 yr; ht=170.9±4.4 cm; wt=68.1±5.2 kg) participated in the study. The subjects were recruited on the basis of availability, lack of pathological knee condition, and ability to perform the exercises without undue stress. All subjects gave informed consent prior to participation. The University Human Subjects Review Committee approved the experimental protocol prior to experimentation.

We used silver chloride surface electrode leads connected to two preamplifiers (P15, Grass Instrument Co) to obtain the EMG signals. The preamplifiers were interfaced to a Macintosh IIci computer. We used the Superscope computer program (GW Instruments, Inc; Somerville, Mass) to filter and rectify raw EMG signals.

Bandwidth was 7 Hz to 6 kHz. The video recording procedures involved a stationary Panasonic Digital 5000 shuttered video camera recording at 30 Hz. The camera was located 30 ft from and perpendicular to the subject's sagittal movement plane. A wide-angle lens allowed the entire movement to be viewed. A 386 Zenith computer with a BCE Associated video controller circuit board was interfaced to the video playback system (Sony PVM 1341 video monitor and Panasonic AG-7300 video cassette recorder). We used a computer program designed by Peak Performance Technologies, Inc to encode sequentially every frame of the tape. The time between any two given frames was determined with an accuracy of 1/60th of a second. To facilitate the location of segmental endpoints during the film analysis, we placed contrasting markers on the joint centers of each subject. We placed black and white plastic tape on the following anatomical landmarks: great toes, right lateral and left medial malleoli, right lateral and left medial tibial condyles, and the right greater trochanter. Each subject reported individually to the laboratory for two experimental sessions. The first session involved practice trials of the various exercises; anthropometric measurements were taken at this time as well. The second session involved EMG and video data collection. We applied the EMG electrodes as closely as possible to the motor end plates of biceps femoris and rectus femoris muscles of the subject's dominant leg, with a 10mm distance between electrode centers. The ground electrode was placed over the fibular head. All hair in the area of electrode placement was removed prior to placement. The subject's skin was scrubbed with an alcohol-soaked gauze pad and electrodes were attached with double adhesive collars.

Subjects completed three maximum isometric contractions each for the extensor and the flexor muscles of their dominant leg. While seated on an N-K table, the knee was positioned and restrained at 45° from full extension for maximum isometric extension trials and at 90° for maximum isometric flexion trials. These contractions provided information needed for initial adjustments of electrodes and amplifiers and baseline data for further contrasts.

Subjects performed six repetitions of each of the following exercises: unilateral one quarter squats (to approximately a 60° angle formed between the upper and lower leg; no external resistance), leg extensions on an N-K table (lifting 25% of body weight), lateral step-ups (20.3 cm step), and movements on the Fitter (two cords if body weight was <73 kg; three cords if >73 kg), Stairmaster 4000 (manual setting, level 7, steady climb), and slideboard (width was two times lower extremity measurement from ASIS to medial malleolus). A reference marker was provided for the subjects during the squat exercise to ensure proper depth of squats. We controlled the speed of movement for each exercise with a metronome (4 seconds per one complete movement of unilateral quarter squats and leg extensions, and 2 seconds per one complete movement of the lateral step-ups, Fitter, Stairmaster, and slideboard movements). The EMG recorder and video camera began recording after the subject had completed three cycles of the exercise under consideration and continued for three more complete exercise cycles. The order of the exercises was counterbalanced among subjects to prevent a treatment effect. There was a 10-minute interval between exercises.

We analyzed the EMG data for both concentric and eccentric phases. Three cycles of EMG data for all experimental conditions were averaged. Using baseline EMG activity (initial isometric contraction data), we calculated percent of maximum EMG activity (%MVC) for each exercise. The percent of maximum values then were used to determine the quadriceps to hamstring ratio. We then analyzed the ratio values using an analysis of variance (ANOVA) with repeated measures. Film data were analyzed for knee joint range of motion. A data smoothing computer procedure (Butterworth digital filter) was applied to the displacement data prior to calculating velocity and acceleration. Following additional statistical analyses with ANOVAs, we determined significant differences in percent of maximum EMG, peak angular velocity, and maximum range of motion as dependent variables. Scheffé's post hoc procedures were applied. A minimum level of significance of p<.01 was chosen.

Results

Mean and standard deviation values for minimum angles achieved and for total range of motion during each exercise are presented in Table 1. ROM was greater during leg extension than during

Table 1.—ROM, Maximum Velocity, and Minimum Angles for the Six Treatment Conditions (mean ± SD)

	range of motion (deg)	maximum velocity (deg/s)	minimum angle (deg)
Fitter	**42.0± 8.6[b,c,f]**	**101.3±27.0**	**25.8±10.3[b,c,d,f]**
Stairmaster	**72.0± 11.7[e]**	**138.8±26.8[d]**	**4.9± 7.8**
leg extension	**80.1± 9.1[d,e]**	**123.4±46.9**	**9.6± 7.1**
quarter squat	**55.9± 6.5**	**91.5±21.7**	**3.2± 4.1**
slide board	**54.8± 10.6**	**162.3±48.5[a,c,d,f]**	**27.6±10.3[b,c,d,f]**
step-up	**68.5± 7.6**	**269.8±41.0[a,b,c,d]**	**5.5± 8.1**

[a] **significantly different (p<.01) than Fitter**
[b] **significantly different (p<.01) than Stairmaster**
[c] **significantly different (p<.01) than leg extension**
[d] **significantly different (p<.01) than quarter squat**
[e] **significantly different (p<.01) than slide board**
[f] **significantly different (p<.01) than step-up**

quarter squat, slideboard, and Fitter exercises and less during Fitter than during Stairmaster and lateral step-up exercises (F[5,179]=24.13, p<.0001; Scheffé, p<.01). In addition, ROM was greater during the Stairmaster exercise than during the slideboard exercise. Fitter and slideboard exercises had similar minimum angles which were larger than all other selected exercises (F[5,179]= 99.99; p<.0001).

Angular velocity means and standard deviation data are presented in Table 1. The greatest angular velocity values were recorded for lateral step-ups (269.8°/s) and the smallest values for quarter squats (91.5°/s; F[5,179]=91.85; p<.0001). The angular velocity of the lateral step-up was greater than all other activities (Scheffé, p<.01). Slideboard values were less than the step-ups and greater than all other exercises except Stairmaster (Scheffé, p<.01). Quarter squat values were smaller than those of the Stairmaster, lateral step-ups, and slideboard (Scheffé, p<.01).

Peak activity of the hamstrings and quadriceps during each activity, expressed as a percentage of each subject's maximum voluntary contraction (%MVC), is presented in Table 2. In addition, the ratio of the activity of the two muscle groups is presented in Table 2 as the hamstring %MVC divided by the quadriceps %MVC.

Mean hamstring activity values ranged from 15.9% MVC for quarter squats to 41.3% MVC for the slideboard. The slideboard was greater than all other activities, and the Fitter greater than the squat and leg extension (F[5,179]=38.57, p<.0001).

Average quadriceps activity ranged from 84.9% MVC for leg extensions to 25.9% MVC for quarter squats. The leg extension %MVC was greater than that of all other exercises, and the slideboard value was different from the quarter squat and Stairmaster values (Scheffé, p<.01; F[5,179]=42.93; p<.0001).

During the leg extension exercise, the hamstrings produced 25.23% as much activity as the quadriceps. In the other five exercises, this percentage was greater than 64%. Hamstring activity as a percentage of quadriceps MVC was less during the leg extension than during the Fitter (F[5,59]=7.85, p<.0001).

Mean and standard deviation values derived from the EMG data for time of contraction of the hamstrings and quadriceps and time of co-contraction of the two muscle groups are shown in Table 3. Significant differences between exercises also are presented in Table 3.

The leg extension exercise produced the longest co-contraction time (2.36 seconds), while lateral step-ups produced the shortest co-contraction time (0.79 seconds). Leg extension values were greater than those of all other exercises, and quarter squats were greater than step-ups, Stairmaster, and

Table 2.—Percent of Maximum Voluntary Contraction (MVC) and Hamstrings to Quadriceps Ratio (mean ± SD)

	% MVC hamstrings	% MVC quadriceps	hamstrings/ quadriceps (%)
Fitter	**27.2±11.1[c,d,e]**	**38.5±17.4**	**70.6**
Stairmaster	**22.6±10.6[c,e]**	**36.0±19.7[d]**	**62.9**
leg extension	**18.2± 8.6**	**84.9±29.6[a,b,d,e,f]**	**21.5**
quarter squat	**15.9± 6.4[e]**	**25.9± 6.8[e]**	**61.5**
slide board	**41.3± 9.0[d,f]**	**55.8±27.3**	**73.9**
step-up	**25.0± 8.0**	**40.9± 9.9**	**61.1**

See Table 1 for key.

Table 3.—Time of Contraction and Co-contraction (second; mean ± SD)

	time of contraction hamstrings	quadriceps (seconds)	time of co-contraction
Fitter	**1.15 ± .22**	**1.31 ± .36**	**0.98 ± .35**
Stairmaster	**0.95 ± .18**	**0.97 ± .24[d]**	**0.81 ± .25[d]**
leg extension	**2.45 ± .29[a,b,e,f]**	**2.70 ± .54[a,b,d,e,f]**	**2.36 ± .32[a,b,d,e,f]**
quarter squat	**1.73 ± .45**	**1.83 ± .36**	**1.65 ± .37[f]**
slide board	**1.49 ± .75**	**1.64 ± .61**	**1.30 ± .72**
lateral step-up	**1.40 ± .52**	**1.41 ± .46**	**0.79 ± .45**

See Table 1 for key.

Table 4.—Total EMG (mV X sec; mean ± SD)

	Total EMG hamstrings	quadriceps
Filter	**0.03 ± .01**	**0.06 ± .01**
Stairmaster	**0.02 ± .004**	**0.04 ± .01[d]**
leg extension	**0.05 ± .01[a,b,e,f]**	**0.12 ± .03[a,b,d,e,f]**
quarter squat	**0.04 ± .01**	**0.08 ± .01**
slide board	**0.03 ± .02**	**0.07 ± .02**
lateral step-up	**0.03 ± .01**	**0.06 ± .02**

See Table 1 for key.

leg extension (F[5,59]=27.532, p<.0001; Scheffé, p<.01).

Mean and standard deviation values for total EMG (area under the curve) derived from EMG data for the hamstrings and quadriceps are presented in Table 4. The leg extension produced the largest hamstrings total EMG (0.052 mV-s), and the Stairmaster produced the smallest hamstrings total EMG (0.02 mV-s). The leg extension value was significantly different than that of all other exercises except the quarter squats (F[5,59]=13.96, p<.0001).

The leg extension produced the greatest quadriceps total EMG (0.116 mV-s), and the Stairmaster again produced the smallest total quadriceps EMG (0.041 mV-s) (F[5,59]=20.82, p<.0001). The leg extension value was significantly different (p<.01) than all other exercises. In addition, Stairmaster was significantly different from squats.

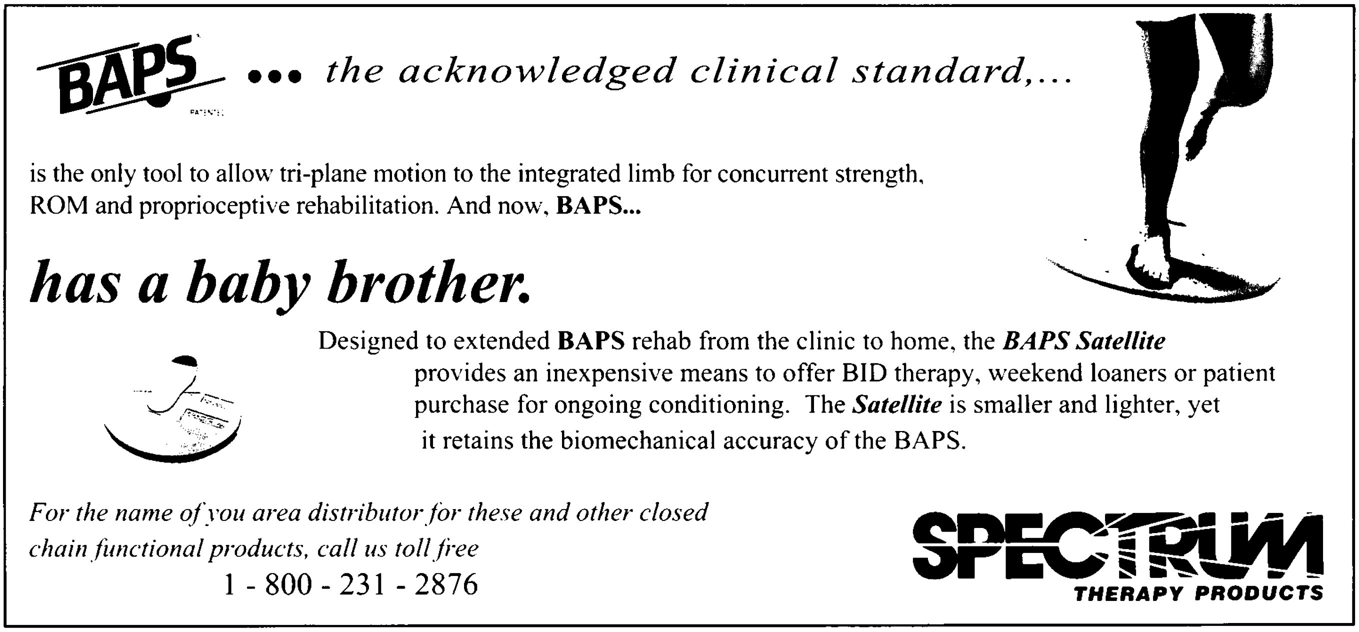
Discussion

The quantification of differences among exercises is dependent upon the speed of movement and the range of movement. Any EMG data difference is dependent upon the nature of the movement. Although the subjects in this study served as their own control, caution is needed when comparing different exercises. During different stages of rehabilitation, speed and degree of movement vary, largely according to the individual's ability to perform in a particular ROM and according to the individual's limits of pain. The differences between exercises as presented here only show one limited movement speed and ROM; healthy subjects were used to help eliminate the variables of ROM and pain.

Several authors[11,16,17,21] have reported a relationship between anterior forces and knee angle. Anterior tibial translation applying elongating straining forces across the ACL occurs at knee angles greater than approximately 70° with quadriceps contraction[18]; therefore, to minimize anterior translational forces, rehabilitation activities should consider ROM values. The kinematic results of this study clearly show a difference in ROM among the selected exercises. The lateral step-ups, the slideboard, the Stairmaster, and the leg extension exercises had maximum angular displacement values greater than 70°.

If full ROM is the selection criteria of a rehabilitation exercise, then the lateral step-up, the leg extension, and the Stairmaster exercises should be considered. These particular exercises allow for movement throughout the entire range of motion allowable at the knee joint. ROM is controlled largely by the individual during rehabilitation, particularly in the early stages, when pain and effusion are factors. In this study, ROM of the quarter squat was controlled experimentally, but the limited ROM achieved on the slideboard and Fitter is a valid concern during knee rehabilitation. While we have concerns about the limited ROM on the slideboard and Fitter exercises, it is clear that both are effective means of improving quadriceps and, particularly, hamstring strength. The data suggest that what might be "lost" in terms of working throughout the entire ROM while using these exercises is outweighed by what is gained in proprioception and the recruitment of other muscle groups (ie, adductors, gluteals). If the slideboard or the Fitter exercises are used, it is important to incorporate another exercise into the rehabilitation protocol that **does** work throughout the ROM.

It is important to increase resistance and ROM as soon as tolerable for each of the closed kinetic chain exercises in order to maximize the strengthening benefits of each. For example, the relatively low quadriceps %MVC for the quarter squat is not particularly surprising, given the limited ROM allowed for this exercise. It does suggest, however, that both ROM and resistance be increased as soon as tolerable, and that the athlete be progressed to the weight room quickly in order to achieve the maximum benefits of the squat exercise.



Resistance and ROM can be increased on any of the closed kinetic chain exercises, which would result in increased muscular contraction and greater strength gains.

The hamstrings play a significant role in providing knee joint stability and are, therefore, of great importance in ACL rehabilitation.[6,14,23,24] In this study, the highest hamstring %MVC occurred during the slideboard exercise. However, magnitude of muscular involvement without consideration of contraction time might lead to a faulty assumption. The total EMG activity values (magnitude X time) might be a more appropriate criterion in rehabilitation technique evaluation. The total EMG difference between exercises was greatest for the leg extension and least for the Stairmaster exercise.

The magnitude of A/P knee shear force is related to quadriceps to hamstring ratio.[5,11,14,17,18] Quadriceps to hamstrings ratios up to 2.25:1 during isokinetic leg extension exercises (30°/s) have been reported.[7] Our EMG-based data at approximately 60°/s indicate a 4.65:1 quadriceps to hamstring ratio for an isotonic leg extension exercise. The relatively high involvement of the quadriceps during the leg extension exercise is supportive of the leg extension being an effective method of strengthening the quadriceps; however, because A/P shear forces are increased during leg extensions, it seems prudent to select alternate exercises to strengthen the quadriceps after ACL reconstruction. The quadriceps to hamstrings ratios of the closed kinetic chain exercises we studied ranged from 1.41:1 to 1.64:1 (Table 3); therefore, our data support the view that the closed kinetic chain exercises studied had lower associated A/P shear forces.

Speed of movement did not appear to influence the quadriceps to hamstrings ratio in closed kinetic chain exercises. The maximum knee velocity for the quarter squat exercise was 91.5°/s, and the maximum knee velocity for the lateral step-ups exercises was 269.8°/s. The hamstring/quadriceps percent values were 61.08% and 61.48%, respectively. Proportional increases in action potentials in both muscle groups might not occur with increases in speed.

Our lateral step-up exercise data do not agree with Brask et al,[3] who reported lateral step-up ratios of 2.78:1 to 2.41:1 between the rectus femoris and biceps femoris and 6.77:1 to 10.65:1 between vastus medialis and semimembranosus/semitendinosus. Based on this evidence, Brask et al concluded that contraction of the hamstring muscles appeared to be of insufficient magnitude to neutralize the A/P shear force produced by the quadriceps femoris muscle. The subjects in the Brask et al study were not athletes, were not of the same gender, and ranged in age from 15 to 30 years. The lack of agreement between our study and the Brask et al study might be related to: 1) differences among subjects, 2) subjects' familiarity with the exercise regimen, 3) subjects' ability to perform a maximum contraction, 4) different muscle groups studied, and 5) cross talk between electrodes.

When selecting an exercise regimen for an individual with an ACL injury, primary considerations are: 1) safety (primarily minimizing A/P shear forces), and 2) the effectiveness of the exercise in strengthening appropriate muscle groups. The closed kinetic chain exercises studied appear to result in minimal shear forces at the knee joint. These exercises also appear to be an appropriate and effective means of improving both quadriceps and hamstrings strength. It is important to closely monitor the program in order to increase ROM and resistance as tolerable for the individual and to, therefore, achieve optimal results. It is equally important to select an effective combination of exercises. It is up to the individual clinician to determine precisely what benefit he/she hopes to derive from each exercise, and how each exercise fits into the rehabilitation protocol designed for each athlete.

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