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Neuromuscular Control of the Knee During a Resisted Single-Limb Squat Exercise

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Abstract

Background—Closed kinetic chain exercises such as single-limb squats are preferred for knee rehabilitation. A complete understanding of the neuromuscular control of the knee during the single-limb squat is essential to increase the efficiency of rehabilitation programs.

Hypothesis—Performing a controlled single-limb squat with resistance to knee flexion and extension will increase the coactivation of the hamstring muscle group, thus reducing the quadriceps/hamstrings ratio.

Study Design—Descriptive laboratory study.

Methods—A total of 15 healthy human subjects (7 women, 8 men) performed controlled single-limb squats in a custom mechanical device that provided resistance to both flexion and extension. Subjects performed the task at 3 levels of resistance, set as a percentage of body weight. Surface electromyographic recordings from 7 muscles (gluteus medius, rectus femoris, vastus medialis oblique, vastus lateralis, biceps femoris, semitendinosus, and medial gastrocnemius) were collected during the task.

Results—Biceps femoris activity during knee flexion increased from approximately 12% maximum voluntary isometric contractions during low resistance (0% body weight) to approximately 27% maximum voluntary isometric contractions during high resistance (8% body weight). Although the quadriceps had greater activity than the hamstrings at all levels of resistance, the quadriceps/hamstrings ratio declined significantly with resistance ($F_{2,27} = 29.05$; $P = .012$) from 3.0 at low resistance to 2.32 at the highest resistance.

Conclusions—Performing controlled resisted single-limb squats may help to simultaneously strengthen the quadriceps and facilitate coactivation of the hamstrings, thus reducing anterior tibial shear forces. The coactivation may also increase the dynamic control of the knee joint.

Clinical Relevance—The typical single-limb squat exercise performed in the clinic does not usually control for bidirectional resistance and knee joint excursion. As seen in this study,

controlled single-limb squats at increased levels of resistance help to increase the coactivation of the hamstring muscles, which is essential to optimize neuromuscular control of the knee.

Keywords

single-limb squat; quadriceps/hamstrings ratio; neuromuscular control; closed kinetic chain exercise

Because of the increased prevalence of knee injury, especially to the ACL,^{4,6} one of the major areas of focus in physical therapy and in sports medicine research has been the dynamic control of the knee. Recovery after knee joint injury is complicated by persistent quadriceps weakness, decreased joint stability, and deficits in proprioception, all of these factors resulting in decreased neuromuscular control.^{11,13,14} During the past decade, knee rehabilitation after ACL reconstruction has undergone a tremendous evolution, from a conservative approach of immobilization for 6 to 8 weeks followed by crutch training for 8 to 12 weeks, to functional rehabilitation that emphasizes immediate motion and weightbearing.²⁶ Proprioceptive training is also gaining recognition as an integral component of rehabilitation.¹⁵ Closed kinetic chain exercises are now increasingly preferred over other exercises because they replicate functional movements such as squatting, stepping, and stair climbing while limiting anterior tibial shear forces and ACL strain.^{19,24} However, there still exists some controversy on this issue. Heijne et al¹⁰ showed that ACL strains were equal and similar to those produced during other rehabilitation exercises such as active extension of the knee. Closed kinetic chain exercises also produce less patellofemoral compressive forces than other exercises, up to knee flexion angles of 60°, and hence can be employed for those patients suffering from patellofemoral dysfunctions at low to midrange knee angles.⁸ Despite these advances in rehabilitation, there still exists a need to design the optimal exercise regimen that would enhance recovery and the full return to normal activity. This result would be possible only with a complete understanding of the neuro-muscular control of the knee during dynamic activities.

One commonly used closed kinetic chain exercise is the single-limb squat (SLS). The SLS is also used as a standard test to assess physical competence.²⁸ It simulates a common athletic position and requires fine control of the body over the fixed lower extremity. One of the primary purposes of this study was to investigate the neuromuscular control of the knee joint during the performance of an SLS exercise.

Analyzing closed kinetic chain exercises such as the SLS is complicated because (1) subjects can use different synergistic strategies to perform the same task,^{7,22} (2) it is difficult to control the speed of the SLS, and (3) there is limited ability to readily adjust the resistance used during the task. Elastic tubing such as Thera-Band (Hygenic Corp, Akron, Ohio), which has color-coded bands with different levels of resistance, is frequently used in rehabilitation to provide resistance training during exercise.^{18,21} Thera-Band is a cost-effective method to apply resistive exercise, but it does not allow a precise dose of resistance and only offers unidirectional resistance to motion when used during the SLS. Applying resistance during both the flexion and extension phase of the SLS may be important for optimizing neuromuscular control of the knee.

Previous reports have not examined the effect of varied resistance during a precise range of motion while performing the SLS.^{2,28} Accordingly, we developed an experimental method that enabled us to apply resistance in both the descending (flexion) and ascending (extension) components of the SLS during a fixed range of motion at a prescribed rate. Our primary goal was to analyze muscle EMG activity during a controlled SLS exercise performed at 3 levels of resistance. We hypothesized that flexion with added resistance would decrease the quadriceps/hamstrings ratio by increasing the activity of the hamstring muscle group.

METHODS

Subjects

Fifteen young, healthy subjects (7 women and 8 men, aged 24.5 ± 3.1 years) with no history of major hip or knee injury or surgery were chosen to participate in this study. Exclusion criteria also included grade 2 or higher ligamentous injuries, meniscal tears, degenerative joint diseases, patellar dislocations, or any fractures of the lower extremity. All subjects were students recruited from the University of Iowa. These subjects participated in sports only for recreational purposes and were not in training for any particular sport at the time of the study. After a brief description of the protocol, subjects signed an informed consent document, which was approved by the institution's Human Subjects Review Board.

Experiment Protocol

The main task was to perform a controlled SLS on the dominant leg (preferred leg to kick a ball). The SLS was performed in a custom mechanical device to the beat of a metronome set at 1 Hz. One complete squat took 2 seconds to finish, with equal times in knee flexion and extension. Preliminary data supported the view that completing the flexion and extension phases of the SLS in 2 seconds was a more accurate way to track the end angles during the 3 different levels of resistance. It was essential to maintain accurate displacements so that we could directly compare the muscle synergies used during the 3 resistance settings. During the task, knee joint excursion was from 0° to 40° of knee flexion. A marker on the computer screen indicated the beginning and end range of motion (0° - 40°). Subjects performed 10 continuous SLS exercises at 3 levels of resistance. The resistance was set as a percentage of body weight (BW). Low resistance was 0% BW, medium resistance was 4% BW, and high resistance was 8% BW. A 3-minute rest period was given between each set of 10 repetitions. Subjects completed a supervised warm-up session for 5 minutes before the experimental protocol.

Instrumentation

We constructed an SLS testing and training system for the purposes of this study (Figure 1). A rack-and-pinion gear system was attached to the anterior knee. The subject performed an SLS, which caused the rack-and-pinion attachment to move linearly in the horizontal plane. The linear displacement was measured by a potentiometer that was mounted on the shaft of the gear and that had been calibrated to convert angular displacement into linear displacement (in centimeters). An electromagnetic braking system with an associated shaft controlled the resistance to the gear. Thus, the brake was directly under current control by a

microcomputer through digital-to-analog input, all under customized software. The resistance of the brake was adjusted according to the subject's BW. This device allowed for minimal translation of the knee joint in the vertical direction. The 0° to 40° knee range of motion made any vertical translation negligible. Visual feedback of the end range of knee displacement (0°-40°) was displayed on a computer screen directly in front of the subject. Linearity, repeatability, and hysteresis of the braking and potentiometer system were within 0.5% of full scale. Surface EMG recordings were collected from 7 muscles: gluteus medius (GM), rectus femoris (RF), vastus medialis oblique (VMO), vastus lateralis (VL), biceps femoris (BF), semitendinosus (ST), and medial gastrocnemius (GA) of the exercised limb. Before affixing the electrodes, the skin was cleaned with alcohol to ensure adequate contact. Silver-silver chloride electrodes (8 mm in diameter) with onsite preamplification (gain $\times$ 35), further amplified at the mainframe computer by 10 000, were placed by a single investigator (R.K.S.) according to the landmarks described by Cram et al.⁵ The amplifier (Model 544, Therapeutics Unlimited, Iowa City, Iowa) used a high-impedance circuit with a common-mode rejection ratio of 87 dB at 60 Hz and a bandwidth of 15 to 4000 Hz.

Data Collection

Before the start of the protocol, 3 maximum voluntary isometric contractions (MVICs) of each muscle were obtained. Subjects were positioned as described by Kendall et al¹² and were asked to hold each MVIC for 3 seconds. Subjects were then placed in the experimental apparatus, and their dominant knee was strapped to the movable segment of the device. An auditory metronome with a beat frequency of 1 Hz was used to time the task. Two lines indicating the desired knee motion range (0°-40°) were made visible on the computer screen to control knee displacement during the task. We provided the subjects with a detailed verbal description of the protocol and allowed 3 to 5 practice trials before the start of the actual experiment. We instructed the subjects to keep the noninvolved leg off the ground by bending at the knee, and the nondominant hand (contralateral to the stance leg) was allowed to rest on a table without being used to support the body's weight. The amount of resistance acting horizontally at the knee is quite substantial and necessitates some light touch support; subjects were therefore instructed to avoid leaning or rotating during the task and were given verbal cues if there were any deviations in the technique or form of exercise during the learning sessions.

Data Analysis

The EMG signals were sampled at a rate of 2000 Hz and analyzed with Datapac II software (version 3.0, RUN Technologies Inc, Laguna Hills, Calif). Because the total knee displacement time was 2 seconds, we divided knee displacement into 100-millisecond bins (approximately 4° of knee angle), creating 10 bins for flexion and 10 bins for extension. We obtained an average of the root mean square EMG for each bin. We analyzed the MVICs by finding the maximum rectified EMG during 1 second of peak contraction. The EMG data were normalized to the percentage of MVIC. Finally, a mean quadriceps/hamstrings (Q/H) muscle ratio was calculated for each subject.

The data from the flexion and extension phases during the study were analyzed independently. We performed a repeated-measures analysis of variance with 2 factors—

muscle and resistance—while using an $\alpha = .05$ level to test for significant differences. The Tukey follow-up test was used to check for simple effects.

RESULTS

A representative example of a single subject's knee displacement and the corresponding EMG signals is shown in Figure 2. All 7 muscles were active during the performance of the SLS exercise. However, the muscles differed in their activation with respect to a change in resistance to knee motion. This difference was indicated by a significant interaction of the muscle and the resistance variables during both flexion ($F_{12,162} = 2.93$; $P = .001$) and extension ($F_{12,162} = 2.26$; $P = .012$) phases. Thus, the way the muscles responded at low resistance was not consistent with how the muscles responded at higher resistances. All EMG values are presented in Table 1.

Follow-up tests indicated that the BF muscle most prominently showed greater activity at increased resistance during the flexion cycle (Figure 3). Among the ham-string muscles, the BF had higher EMG activity at all 3 levels of resistance when compared to the ST muscle ($P < .05$). Activity of the ST was consistent across all 3 resistance levels during both flexion and extension (approximately 7%). The 3 quadriceps muscles showed increased EMG activity from medium to high resistance ($P < .05$) but not from low to medium resistance (Figure 4). Among the quadriceps muscles, the VMO showed the highest activity as resistance was increased. The GA and the GM muscles were similar across all resistances.

An important finding of this study was the noticeable co-contraction of the hamstring muscles and quadriceps muscles during the entire task. However, the activity of the quadriceps muscles was greater than the hamstring muscles at all levels of resistance. This result was due to the significant increase in BF activity with increased resistance (Table 1).

DISCUSSION

In recent years, there has been a significant increase in the use of closed kinetic chain exercises for knee rehabilitation.⁹ Studies have shown that closed kinetic chain exercises help strengthen the quadriceps while producing low anterior tibial shear forces,^{9,24,25} and they produce lower patellofemoral compressive forces when compared to open kinetic chain exercises.⁸ These exercises replicate functional activities, thus enhancing an early return to normal activity. In the present study, we examined the EMG recordings of 7 muscles during controlled SLS, a frequently used closed kinetic chain exercise. Although a few earlier studies have examined the kinematic and EMG activity of the SLS,^{2,28} the novelty of this study was the performance of controlled SLS at various levels of resistance applied at a fixed rate in both knee flexion and extension.

The typical SLS relies on body weight to provide a resistive load during both the knee flexion and knee extension phases. During the knee flexion phase, body weight (or Thera-Band around the posterior knee for additional resistance) serves to pull the subject into the knee-flexed position. The nervous system likely activates the quadriceps muscles initially, then progressively decreases quadriceps activity to allow the knee to flex under a lengthening muscle contraction. During the knee extension phase, body weight (or Thera-

Band around the posterior knee) resists the subject's movement into knee extension. The extension phase of the exercise is often emphasized for strengthening the quadriceps muscles in clinical practice.

The SLS exercise examined in this study was different from the typical SLS for several reasons. First, resistance was applied so that the individual resisted rather than assisted during the knee flexion phase of the exercise. Accordingly, the subject had to consciously activate the hamstring muscles in an effort to initiate knee flexion. As the results of this study indicate, the biceps femoris activity was scaled according to the level of resistance applied during this unique flexion phase of the exercise. Second, the rate and the excursion of the SLS exercise were controlled by having the subjects keep cadence to a metronome and by feeding back the end points of the flexion and extension phases through a visual target on the computer screen, respectively. Finally, each subject worked against a resistance that was individualized as a percentage of his or her own body weight.

The 2 major findings of this study were that the biceps femoris stayed active during the entire SLS and that the Q/H ratio decreased with an increase in resistance. Coactivation of the hamstrings decreases the amount of anterior tibial shear forces, thus acting as an ACL protagonist.²⁴ The Q/H ratio is a common parameter used to describe the synergistic activity around the knee joint.¹ This ratio is used to indicate the ability of the hamstrings to counteract the anterior tibial forces exerted by the quadriceps. The Q/H ratio in our study ranged from 2.32 to 3.0. Values for conventional isokinetic Q/H ratios have been estimated to be around 2 to 2.5.¹

Beynon and Fleming³ affixed in vivo strain transducers to the ACL and showed that ACL shear forces are low during exercises that are dominated by the hamstring muscle group. They showed that ACL strain values produced during squatting were less than those produced during active knee flexion and extension. More et al¹⁹ replicated squatting in a cadaveric model and showed that the addition of hamstring activity decreased the amount of anterior tibial translation and internal tibial rotation during knee flexion.

In support of the high levels of quadriceps and ham-string activity achieved during 1-legged squats and step-ups, Beutler et al² suggested that these exercises are very effective in increasing muscular strength. Ohkoshi et al²⁰ suggested that exercise in a standing position is safe for rehabilitation during the early stages of ACL reconstruction because co-contraction of the quadriceps and ham-strings occurs and because negligible anterior shear forces were noticed during standing with knees flexed (similar to a half-squat) at various angles of knee flexion. Wilk et al²⁶ noticed greater co-contraction of the quadriceps and ham-strings during the performance of a squat than during open kinetic chain exercises such as knee extension. Stensdotter et al²³ showed that closed kinetic chain exercises produce more simultaneous activity than open kinetic chain exercises, with earlier onset and more activity of the VMO. A predisposing factor for patellofemoral pain syndrome (PFPS) is a lateral-tracking patella. Thus, Stensdotter et al²³ suggested that closed kinetic chain exercises, which increase the activity of the VMO, should be prescribed for those suffering from PFPS. In the present study, the 3 components of the quadriceps contributed equally during the task, except for the VMO, which showed greater activity at the highest resistance

level. A weak VMO results in lateral patellar dislocation because of the pull of the stronger VL.¹⁶ Hence, this controlled SLS could strengthen all the quadriceps muscles equally and could also help to specifically train the VMO at higher resistances.

Escamilla et al⁸ noticed increased patellofemoral compressive forces during open kinetic chain exercises at knee angles less than 60°. However, closed kinetic chain exercises generated more forces than open kinetic chain exercises at knee angles greater than 85°. In our study, the SLS exercise was performed at knee angles of 0° to 40° of flexion. Thus, the patellofemoral compressive forces might have been minimal when the exercise was performed at low resistance. At the higher resistances (4% BW and 8% BW), the knee joint might have experienced greater patellofemoral compressive forces. The amount of resistance that can safely be used on this instrument for patients with patellofemoral dysfunction needs further study.

Patients with ACL-reconstructed knees compensate for knee extension-moment deficits with hip and ankle extensors.⁷ Within a year after ACL reconstruction, patients are shown to use different strategies on their involved limb to perform a squatting task.²² Equal hip and knee extensor moments have been seen in the noninvolved leg, while an increase in hip extensor moment and a decrease in knee extensor moment have been noticed in the affected extremity. In ACL-deficient subjects, diminished specificity of muscle action has also been noted, leading to a deterioration of performance during dynamic knee-stability tasks due to the difficulty in controlling force production and to increased joint stiffness.²⁷ Hence, ACL rehabilitation should focus on exercises involving the affected leg to prevent strength and performance deficits. The SLS exercise used in this study, which provided resistance in both the flexion and extension phases, required neuromuscular control throughout the exercised range. The complexity of the task was increased by the addition of resistance to knee flexion and extension, compelling the subject to coactivate the muscles of the knee. We believe that resistance imposed during the flexion phase causes the nervous system to coactivate the limb differently than if it were moved in the same direction of a prescribed load. A previous report indicated that the quadriceps muscles are the primary musculature activated during the flexion phase of the typical SLS exercise.²⁸ Future investigations will explore the extent to which injury and gender influence these synergistic patterns.

Many studies have shown that women are more prone to ACL injury than men; numerous factors have been identified in this regard.¹⁷ In our study, we did not have a sufficient sample size to make any assertions about gender differences in muscle recruitment and activity. A preliminary assessment, however, supports the view that women have less biceps femoris activity than men during both flexion and extension phases of the SLS. Zeller et al²⁸ found women to have higher rectus femoris activity during the extension phase of the SLS, suggesting that this increase may lead to more stress on the ACL. Gender differences in the performance of this SLS exercise are currently under investigation.

CONCLUSION

In this study, we examined the effect of various levels of resistance applied bidirectionally during an SLS exercise. Increased resistance augmented quadriceps activity in both

directions but also augmented biceps femoris activity during the knee flexion phase of the exercise. Performing the SLS exercise under controlled conditions, as used in this study, may help to increase the dynamic control of the knee joint through synergistic activation patterns needed for flexion perturbations during gait. The adjustability of this method will allow future investigations to evaluate the effects of various resistance patterns on the neuromuscular control strategies used around the knee.

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Figure 1.
Schematic diagram of the single-limb squat testing system.

Figure 2.

Representative example from 1 subject showing knee displacement and raw EMG data of 7 muscles during the single-limb squat at low resistance. ST, semitendinosus; BF, biceps femoris; RF, rectus femoris; VMO, vastus medialis oblique; VL, vastus lateralis; GM, gluteus medius; GA, medial gastrocnemius.

Figure 3.

Root mean square EMG records (expressed as a percentage of maximum voluntary isometric contractions [% MVIC]) of the semitendinosus (ST) and biceps femoris (BF) at low resistance (A), medium resistance (B), and high resistance (C). The x-axis is broken into time bins of 100 milliseconds (approximately 4° of knee angle), and each graph shows the average of 10 repetitions during an entire single-limb squat. Bins 1 to 10 indicate flexion, and bins 10 to 20 indicate extension. Data points are means of all 15 subjects; error bars are standard errors.

Figure 4.

The EMG activity (expressed as a percentage of maximum voluntary isometric contractions [% MVIC]) of the rectus femoris (RF), vastus medialis oblique (VMO), and vastus lateralis (VL) at low resistance (A), medium resistance (B), and high resistance (C). The x-axis is broken into time bins of 100 milliseconds (approximately 4° of knee angle), and each graph shows the average of 10 repetitions during an entire single-limb squat. Bins 1 to 10 indicate

flexion, and bins 10 to 20 indicate extension. Data points are means of all 15 subjects; error bars are standard errors.

TABLE 1

Root Mean Square EMG Data^a

	<u>Flexion</u>		<u>Extension</u>		<u>Full Cycle Ratio</u>	
	Mean	SD	Mean	SD	Mean	SD
Low resistance (Q/H ratio = 3.0)						
Hamstrings	9.1	7.9	5.9	6.0	7.6	7.2
Semitendinosus	6.6	4.4	5.2	4.6		
Biceps femoris	11.7	4.5	6.7	7.0		
Quadriceps	29.8	56.0	25.4	23.2	27.6	43.1
Rectus femoris	36.6	94.2	19.3	12.1		
Vastus medialis oblique	29.6	15.6	24.6	11.5		
Vastus lateralis	23.2	15.0	32.3	35.6		
Gluteus	18.8	14.5	12.8	4.6	15.8	11.9
Gastrocnemius	10.9	9.8	10.7	8.67	10.85	9.27
Medium resistance (Q/H ratio = 2.76)						
Hamstrings	10.8	10.5	8.6	8.8	9.4	9.6
Semitendinosus	8.4	8.7	7.3	8.0		
Biceps femoris	13.2	11.5	9.9	9.5		
Quadriceps	25.6	26.5	26.8	22.7	26.0	24.2
Rectus femoris	22.8	26.6	30.7	31.1		
Vastus medialis oblique	26.5	11.7	28.9	18.1		
Vastus lateralis	27.6	35.6	20.8	14.6		
Gluteus	11.7	6.4	16.6	7.9	14.1	8.8
Gastrocnemius	9.1	6.9	10.9	7.9	10.05	7.5
High resistance (Q/H ratio = 2.32)						
Hamstrings	18.2	16.5	11.0	10.6	14.2	14.0
Semitendinosus	9.2	8.0	7.7	5.9		
Biceps femoris	27.1	17.9	14.4	13.0		
Quadriceps	27.9	30.0	38.1	34.7	32.9	32.1
Rectus femoris	17.0	14.2	35.7	35.5		
Vastus medialis oblique	31.5	16.3	43.6	41.3		
Vastus lateralis	35.2	45.2	35.0	24.3		
Gluteus	17.2	10.2	21.2	5.9	19.2	10.7
Gastrocnemius	15.8	14.4	14.0	9.7	14.9	12.3

^aData are expressed as a percentage of maximum voluntary iso-metric contractions. Note the decrease in quadriceps/hamstrings (Q/H) ratio with an increase in resistance.