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Electromyographic Analysis of Exercises Proposed for Differential Activation of Medial and Lateral Quadriceps Femoris Muscle Components

Background and Purpose. The purpose of this study was to determine whether active exercises combining hip adduction with knee extension activate medial components of the quadriceps femoris muscle (QF) more than does knee extension alone. **Subjects.** Twelve healthy adults (6 men, 6 women), aged 20 to 36 years ($\bar{X}=24.8$, $SD=5.8$), participated in the study. **Methods.** The subjects performed quadriceps femoris setting (QS), straight leg raising (SLR), straight leg raising with the hip laterally rotated (SLR/LR), and straight leg raising combined with isometric hip adduction (SLR/ADD). Electromyographic (EMG) activity was recorded from the oblique (VMO) and longitudinal (VML) portions of the vastus medialis, vastus lateralis (VL), and rectus femoris muscles. **Results.** Comparison of normalized mean EMG magnitudes revealed that the single-joint QF components (VMO, VML, and VL) demonstrated significantly greater activity during QS than during any of the three SLR variations and that SLR/LR and SLR/ADD did not elicit greater relative activity of medial QF components than did QS or SLR.

Conclusion and Discussion. These findings do not support the notion that concurrent use of the hip adductors during knee extensor exercises results in preferential strengthening of the VMO. [Karst GM, Jewett PD. Electromyographic analysis of exercises proposed for differential activation of medial and lateral quadriceps femoris muscle components. *Phys Ther.* 1993;73:286-299.]

Key Words: Electromyography; Exercise, strengthening; Kinesiology/biomechanics, lower extremity; Knee.

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Weakness and atrophy of the quadriceps femoris muscle (QF) are commonly associated with a wide variety

of traumatic and pathological conditions involving the knee, and active exercises aimed at strengthening the

QF have long played a prominent role in the rehabilitation of patients with knee disorders. A wide variety of static and dynamic exercise regimens have been shown to be effective for increasing the extensor torque-producing capabilities of the QF group as a whole,¹⁻³ and a number of studies have compared the relative effectiveness of various exercises in terms of the extent and rapidity of those increases.^{2,4-6} Though the rate and magnitude of gains in QF torque production are undeniably important considerations in the choice of an appropriate strengthening regimen, it has become apparent that other con-

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siderations should enter into that choice. For example, modifications of QF strengthening protocols have been proposed for reducing stress to specific joint structures, such as the inferior surface of the patella in patients with chondromalacia patellae.⁷⁻⁹

Biomechanical analyses suggest that normal alignment and function of the patellofemoral joint appear to depend on an appropriate balance of medial and lateral forces exerted on the patella by passive structures (eg, the patellar retinacula) and by active muscular forces.⁹ Imbalance of the medial and lateral forces acting on the patella is thought to be an important etiological factor in a number of patellofemoral disorders. Most commonly, the net force on the patella is directed too laterally, resulting in predisposition to lateral subluxation or dislocation of the patella and to degenerative disorders such as chondromalacia patellae.⁹⁻¹¹ Treatment for such problems is generally aimed at increasing the medial force relative to the lateral force acting on the patella.^{8,9,11-14}

Approaches to increasing the ratio of medial to lateral forces acting on the patella have included both conservative techniques, such as biofeedback,^{15,16} electrical stimulation,⁷ taping,¹⁴ and active exercise,^{8,9,11,14} and surgical techniques,¹⁷ such as lateral retinacular release or plication of the vastus medialis obliquus component (VMO).

Variations in muscle fiber orientation and attachment to the patella result in marked differences in the direction of the force vectors exerted by various QF components. Studies of muscle fiber orientation^{13,18,19} suggest that the vastus lateralis muscle (VL) force component is directed 12 to 15 degrees laterally with respect to the femoral shaft, whereas the VMO force is directed 40 to 55 degrees medially and that of the vastus medialis longus component (VML) is directed 15 to 18 degrees medially. These studies supply the rationale for prescribing active strengthening exercises that preferentially activate the medial QF components, especially the VMO, to a greater

degree than the lateral components. Evidence for the efficacy of these particular exercise regimens, however, is lacking. The focus of this study is on specific active exercises that have been proposed for selective strengthening of the QF components that contribute significantly to the medially directed forces on the patella.

In the early 1950s, Wheatley and Jahnke²⁰ suggested that the VMO was responsible for the terminal phase of knee extension, and thus selective VMO activation could be achieved by limiting isotonic exercises to the last few degrees of knee extension. This selective action theory has since been refuted by a number of electromyographic (EMG) studies demonstrating that all QF components are active throughout the range of knee extension. (For a discussion of this controversy, readers are referred to a 1977 review by Speakman and Weisberg.²¹)

More recently, exercises combining activity of the hip adductors in conjunction with knee extensor strengthening activities have been advocated as a means of preferentially activating and exercising the VMO.^{14,22-24} Specific exercises proposed include straight leg raising performed with the hip in lateral rotation²² (SLR/LR) as well as isometric hip adduction exercises in conjunction with conventional knee extensor strengthening exercises²⁴ such as straight leg raising combined with isometric hip adduction (SLR/ADD). The most frequently cited rationale for such exercises is an anatomical linkage between the VMO and the hip adductor muscles.^{14,22-24} Based on anatomical studies indicating that many of the VMO fibers originate from the tendon of the adductor magnus muscle,^{18,19} it has been suggested that concurrent activation of the hip adductors with the QF group would provide the VMO with a more stable proximal attachment, and thus facilitate preferential activation of that component of the QF group.^{14,22-24}

Though this proposed rationale seems plausible, convincing evidence that the specific exercises that have been proposed for concurrent activation of

knee extensors and hip adductors (eg, SLR/LR or SLR/ADD) actually result in measurable increases in the VMO to VL activation ratio is not found in the literature. Hanten and Schulthies²³ have reported that an increased VMO to VL activation ratio results from performing isolated hip adduction exercises, suggesting a functional link between the VMO and the hip adductor muscles. Their study, however, did not directly test the SLR/LR or SLR/ADD exercises used clinically, because subjects were positioned with the knee in 60 degrees of flexion and were only instructed to perform isometric hip adduction rather than concurrent hip adduction and knee extension. Basmajian²⁵ and Wild and associates,²⁶ however, provide anecdotal evidence suggesting that the SLR/LR does *not* change the relative activity pattern of the QF components, though neither of those reports provide data directly supporting that claim.

In this study, quantitative EMG techniques were used to assess the relative activity levels of various QF components during conventional quadriceps femoris setting (QS) and straight leg raising (SLR) exercises and during two variations of SLR that require concurrent hip adductor activation (SLR/LR and SLR/ADD). By studying these four exercises, we were able to address the following questions:

1. Do the relative activity levels of the various QF components remain fixed during volitional QF strengthening exercises, or can specific exercises vary the relative contribution of those components?
2. Do specific exercises that have been advocated for preferential strengthening of the VMO on the basis of a proposed functional link between activation of the hip adductor muscles and the VMO actually result in a greater VMO to VL activity ratio than conventional QS or SLR exercises?

Though the clinical efficacy of these exercise techniques must ultimately

Table 1. Descriptive Statistics for Subject Characteristics

Subjects	Height (cm)			Weight (kg)			Age (y)		
	\bar{X}	SD	Range	\bar{X}	SD	Range	\bar{X}	SD	Range
Female (n=6)	172	10.2	158–185	63.5	5.9	56.8–72.6	22.5	3.3	20–29
Male (n=6)	184	6.1	175–193	82.8	6.6	74.8–93.1	27.0	7.1	20–36
Total (N=12)	178	10.1	158–193	73.2	11.7	56.8–93.1	24.8	5.8	20–36

be assessed by studying a patient population, we chose a population without knee pathology for our initial study of these exercises for two main reasons. First, the anatomical linkage between the VMO and the hip adductors, which is the purported mechanism by which these exercises might enhance VMO activity, should be equally present in both healthy subjects and patients with patellofemoral dysfunction. As such, any effects on VMO activity attributable to concomitant hip adductor activation should be observable in both healthy and patient populations. Furthermore, a previous investigation of QF activity patterns during QS and SLR exercises²⁷ did not reveal significant differences between healthy subjects and those with knee pathology, suggesting that knee pathology does not necessarily alter the neural activity patterns of the QF group. Given these considerations, quantifying the effects of these exercises in a healthy population seems a logical first step in determining clinical efficacy.

Method

Subjects

Twelve subjects (6 women, 6 men) with no current knee pathology volunteered to participate in this study. Descriptive statistics pertaining to height, weight, and age are presented in Table 1. Each subject provided informed consent prior to participating in the study.

Electromyographic Procedures

Electromyographic activity was recorded using a bipolar configuration and silver-silver chloride surface electrodes. Following skin preparation by removal of excess hair and cleansing with isopropyl alcohol, pairs of electrodes were applied to the skin over the VMO, VML, VL, and rectus femoris muscle (RF). A common reference electrode was placed on the patella, and the thigh was wrapped in an elastic bandage to prevent movement-related artifacts. Electrode placement was standardized based on a modification of the technique proposed by Zipp²⁸ for the vastus medialis muscle. Figure 1 illustrates the typical location and orientation of these electrode pairs.

Electromyographic signals were differentially amplified using high-performance bioamplifiers (Model 575-03)* having a bandwidth of 0.1 to 20,000 Hz and a maximum gain of 100,000. After conventional band-pass filtering (100–1,000 Hz), the EMG signals were full-wave rectified and smoothed using a contour-following integrator (Model S76-01)* (time constant 15 milliseconds) to obtain the linear envelope of the EMG signal. The rectified and smoothed signals were then digitized[†] on-line at a sampling rate of 500 Hz, and the EMG data were stored on magnetic media for later analysis.

Subjects were positioned supine on a standard treatment table. At the foot of the table, a cardboard background with two foot silhouettes placed 25 cm above the table surface served as a target during the SLR exercises. One silhouette was vertical so that the subject would maintain the hip in 0 degrees of rotation for the SLR and SLR/ADD exercises, and the second outline was rotated 45 degrees laterally to serve as the target for the SLR/LR exercise (Fig. 2). To allow for visual alignment of the foot with the target silhouette while maintaining constant head and body position, the subject's head was supported with the neck in slight flexion.

All exercises were performed with the right lower extremity. The contralateral lower extremity was placed in 45 degrees of hip and knee flexion, and the pelvis was stabilized with a restraining strap across the iliac crests. During all variations of the SLR exercise (SLR, SLR/ADD, and SLR/LR) resistance was added by applying ankle weights equivalent to 5% of body weight. For the SLR/ADD exercise, an external torque tending to abduct the hip was applied via a rope and pulley apparatus attached just distal to the malleoli (Fig. 2). The apparatus was adjusted for each subject so that it provided a lateral force (equivalent to 5% of body weight) acting at a right angle to the tibia during the isometric hold phase of the exercise.

Standardized verbal instructions were given prior to the first repetition of each exercise. These instructions were provided by the same investigator for all 12 subjects. The four exercises performed in this study were:

1. Quadriceps setting (QS): Subjects were instructed to maximally activate their thigh muscles in order to straighten their knee and were provided with the prompt "tighten" and a two count, by which time they were to attain and hold a maximal contraction. At the completion of the 5-second data-

*Coulbourn Instruments, Box 2551, Lehigh Valley, PA 18001.

†WATSCOPE, Northern Digital Inc, 403 Albert St, Waterloo, Ontario, Canada N2L 3V2.

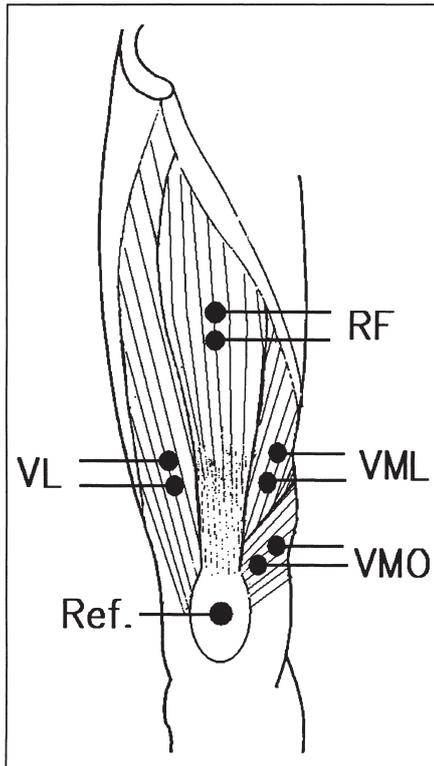


Figure 1. Representative electrode placements for bipolar surface electromyographic (EMG) electrodes and common reference electrode (Ref). The EMG activity was recorded from four components of the quadriceps femoris muscle: rectus femoris (RF), vastus lateralis (VL), vastus medialis obliquus (VMO), and vastus medialis longus (VML).

collection period, subjects were directed to relax.

2. Straight leg raising (SLR): Subjects were instructed to perform a maximal QS exercise prior to the lifting phase of this exercise. Subjects were provided with the prompts "tighten . . . lift" and an additional two count, by which time they were to align their foot with a target foot silhouette. Subjects were instructed to maintain that position until the investigator indicated the completion of the trial, 5 seconds after reaching the designated position.
3. Straight leg raising with lateral rotation of the hip (SLR/LR): Subjects

began in and maintained 45 degrees of lateral rotation at the hip for this exercise. Instructions were identical to those for the SLR exercise except that subjects were directed to align their foot with a background target rotated 45 degrees clockwise from vertical.

4. Straight leg raising with isometric hip adduction (SLR/ADD): This exercise was identical to the SLR exercise except that an external abduction torque acted on the hip via a rope and pulley apparatus, as illustrated in Figure 2.

The exercise session was initiated with five repetitions of the QS exercise. The subject then sequentially performed one repetition each of the SLR, SLR/LR, and SLR/ADD exercises until a total of five repetitions of each SLR variation was completed. The session was concluded with an additional five QS repetitions. Subjects were allowed to perform a practice trial of each exercise before data collection was begun. A rest period of approximately 30 seconds was given between repetitions in order to minimize fatigue, and subjects were instructed to notify the investigators of any fatigue or discomfort associated with the exercises.

Data Analysis

The magnitude of EMG activity for each repetition of each exercise was quantified by digital integration of the smoothed and rectified signals over the 5-second *isometric phase* of the exercise, as illustrated in Figure 3. Within-subject reliability of the EMG measures was established by calculating intraclass correlation coefficients (ICC[1,1]) using a one-way analysis of variance (ANOVA) model, as described by Baumgartner.²⁹ Two aspects of the experimental protocol were designed to exclude the possibility of fatigue, practice, or learning effects. First, we attempted to eliminate any differential effects of fatigue

by having subjects perform single repetitions of the three SLR variations sequentially rather than in a single block of five repetitions and by allowing for rest between repetitions. Second, two sets of the QS exercise were performed, one at the start of the session and one at the end.

Linear regression analysis[‡] of mean EMG activity for the initial and final sets of the QS exercise was used to examine the possibility that the results might be affected by factors such as fatigue, learning, and changes in electrode impedance. In order to allow for comparisons across subjects, mean EMG values for each QF component were then normalized relative to the maximum value obtained for that muscle during any of the exercises performed by that subject. Based on the normalized mean EMG activity, medial to lateral activity ratios (VMO to VL and VML to VL) were calculated for each exercise. A repeated-measures one-way ANOVA was used to test for between-group (ie, between-exercise) effects, and *post hoc* multiple comparisons were made using paired-samples Bonferroni confidence intervals³⁰ with the alpha level established at .05.

Results

Intraclass correlation coefficients of within-subject reliability for each of the four QF components for five sets of exercises are shown in Table 2. The ICCs for all comparisons were greater than .92, with a mean reliability coefficient of .979 over all 20 comparisons. Because this model treats all sources of variation other than differences among subjects as a lack of reliability, the high correlation coefficients indicate a high degree of intrasubject reliability and we believe justify our use of the mean value of the five repetitions of each exercise for each subject in subsequent analyses. Linear regression of initial QS EMG values on final QS EMG values also demonstrated a high degree of repeatability, as indicated by the high correlation coefficient ($R=.97$) and a slope of very nearly 1.00 ($y=0.998x-0.0004$), indicating that effects attributable to fa-

[‡]SYSTAT, version 4.2, SYSTAT Inc, 1800 Sherman Ave, Evanston, IL 60201.

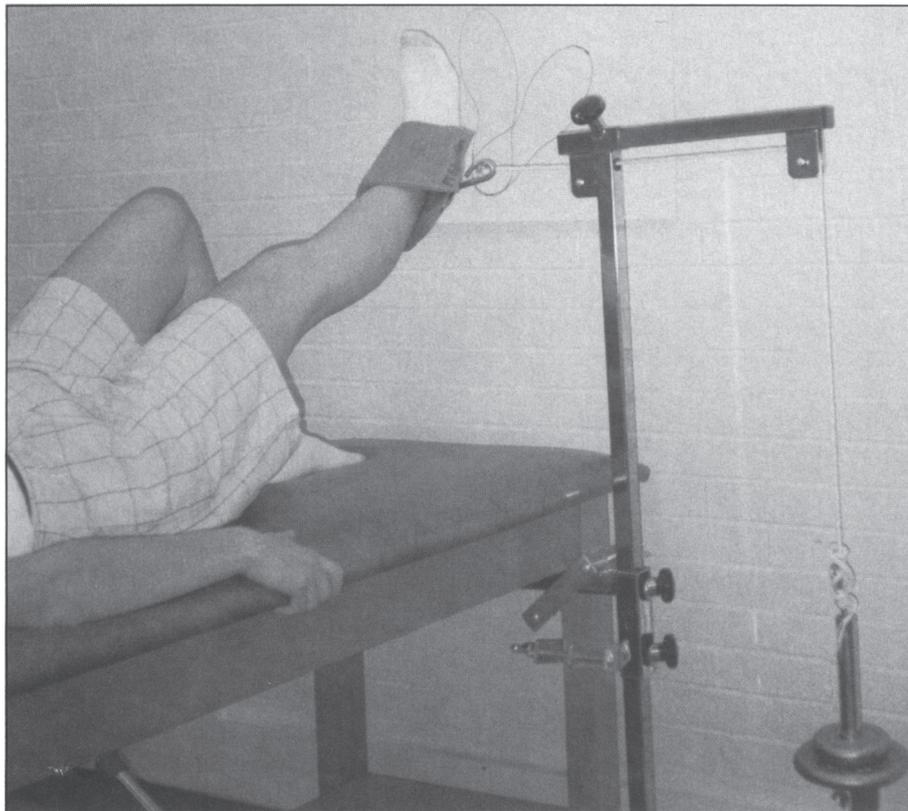


Figure 2. Mechanism for application of lateral forces to the lower extremity during the straight leg raising with isometric hip adduction (SLR/ADD) exercise. Ankle-cuff weights provide additional resistance to hip flexion and knee extension, while the rope and pulley arrangement provides a laterally directed force at the ankle, resulting in abduction torques about the knee and hip. Visual alignment with the appropriate foot silhouette provides consistent positioning in either neutral position (for the straight leg raising and SLR/ADD exercises) or in 45 degrees of hip lateral rotation (for the straight leg raising with hip laterally rotated exercise).

tigue, learning, or changes in electrode impedance were minimal.

The data for each subject and each muscle group were normalized with respect to the highest mean EMG value recorded from that muscle group during any of the exercise conditions. For 10 of the 12 subjects, the QS exercises elicited the greatest mean EMG activity in each of the single-joint QF components (VMO, VML, and VL). Figure 4 illustrates the relative activity of each of the four QF components tested during each set of exercises. Figure 4 shows that each of the single-joint QF components (VMO, VML, and VL) demonstrated similar patterns of activity across the various exercises, whereas the two-joint RF exhibited a very different pattern of activity.

There was a significant ($P < .05$) between-group (ie, between-exercise) effect for each of the four QF components studied. *Post hoc* analyses using paired-sample Bonferroni confidence intervals³⁰ revealed that for the VMO, VML, and VL, both the initial and final QS exercises elicited significantly greater activity than any of the three SLR variations ($P < .05$). There were no significant differences between the mean activity levels of any of the single-joint knee extensors when comparing the initial and final QS exercises or when comparing the three variations of the SLR exercise. In comparison with the single-joint QF components studied, the two-joint RF exhibited marked differences in activity patterns. The SLR elicited significantly greater RF activity than did the initial QS or SLR/ADD exercises

($P < .05$), and the SLR/LR exercise elicited significantly greater RF activity than did the SLR/ADD exercise or either set of QS exercises ($P < .05$).

In order to more closely examine the relative activity of medial and lateral QF components, VMO to VL and VML to VL ratios were calculated using the normalized mean EMG data. Figure 5 illustrates the comparison of normalized mean medial to lateral EMG ratios for both the oblique and longitudinal components of the vastus medialis muscle. A one-way ANOVA revealed that there were no significant exercise-dependent effects on either the VMO to VL or VML to VL ratio.

Discussion

Rationale for Design and Implementation

This study was designed to quantify the relative activity levels of various QF components during exercises that have been proposed for preferential strengthening of the VMO. More generally, the study was designed to test the notion that a functional link exists between activity of the hip adductor muscles and a relative increase in activity of medial QF components.

The methodology chosen for this study was based on the implicit assumption that the relative magnitude of the EMG for each QF component during a given exercise is indicative of the strength gains that may be expected in that component as a result of training with that exercise. That assumption appears justified for several reasons. All data for each subject were collected in a single session in order to ensure that electrode placement and amplification were unchanged across exercises, and the data were appropriately normalized before analyzing data. Intraclass correlation coefficients demonstrated the trial-to-trial reliability of the EMG measures, and EMG magnitudes for initial and final QS sets showed virtually no change, indicating that effects attributable to fatigue, learning, or changes in skin-electrode interface characteristics were negligible in this

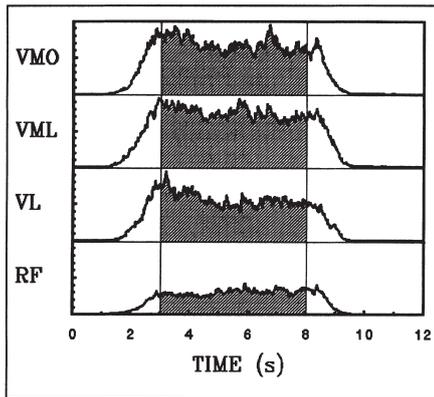


Figure 3. Representative plot of rectified and smoothed electromyographic (EMG) activity recorded from four quadriceps femoris muscle components (VMO=vastus medialis obliquus, VML=vastus medialis longus, VL=vastus lateralis, RF=rectus femoris) during the performance of a single quadriceps femoris setting exercise. Mean EMG amplitude for each muscle component was calculated over the 5-second period indicated by the shaded region, during which time the subject was instructed to maintain a maximal voluntary contraction.

study. Most importantly, all comparisons of EMG magnitude were carried out only for the isometric phase of each exercise, during which the magnitude of the rectified and smoothed EMG signal has been shown to be proportional to the force exerted by a given muscle^{31,32} and thus, in accordance with the overload principle, to the strength gains to be expected from the performance of that exercise.

Table 2. Intraclass Correlation Coefficients for Each of the Quadriceps Femoris Muscle Components Over Each of the Five Sets of Exercises

Exercise ^a	Muscle Component ^b			
	VMO	VML	VL	RF
QS (initial)	.992	.996	.992	.967
SLR	.950	.986	.983	.991
SLR/LR	.971	.982	.971	.975
SLR/ADD	.977	.991	.991	.982
QS (final)	.981	.992	.986	.928

^aQS=quadriceps femoris setting; SLR=straight leg raising; SLR/LR=straight leg raising with hip laterally rotated; SLR/ADD=straight leg raising combined with isometric hip adduction.

^bVMO=vastus medialis obliquus; VML=vastus medialis longus; VL=vastus lateralis; RF=rectus femoris.

The specific exercises that were chosen for study included two of the most commonly prescribed exercises for general QF strengthening, QS and SLR,¹¹ as well as two variations of the SLR that elicit concurrent hip adductor activity and that have been suggested as means of preferentially strengthening the VMO to a greater degree than the VL. The QS exercises were included because they are commonly used in the treatment of patellofemoral disorders and because our pilot studies, as well as data from previous investigations,^{27,33} indicated that the QS exercise consistently elicits the greatest activity of the single-joint knee extensors in most subjects.

Comparison of QF activity across the three variations of the SLR provides the most direct test of the proposed functional link between VMO activity and hip adductor activity. The SLR/LR exercise has been specifically suggested as a means of preferentially strengthening the VMO²² and has the advantage of being a relatively simple modification of the SLR exercise for the patient using a weighted boot or ankle-cuff weight for added resistance. Laterally rotating the hip, however, not only alters the muscular torque requirements at the hip, but also reduces the magnitude of knee extensor torque required to maintain complete knee extension. In the position used in this study (45° of lateral hip rotation), the forces attributable to

gravity acting on the shank, foot, and cuff weight contribute approximately equally to flexion and abduction torques about the knee. The abduction torque about the knee could be opposed by passive structures, such as the medial collateral ligament, rather than by active muscle forces. Direct comparison of RF EMG activity between SLR and SLR/LR conditions is further confounded by the possibility of length or moment arm changes for that two-joint muscle. For the reasons outlined above, we included the SLR/ADD exercise in this study. By simply adding to the SLR exercise a laterally directed force at the ankle, activation of the hip adductors could be achieved without any alteration in the required hip flexor or knee extensor torques and without altering either the length or moment arm of any of the QF components. Thus, comparison of medial to lateral activity ratios elicited by the SLR and SLR/ADD exercises provides the most direct test of the notion that VMO activity is enhanced by concurrent hip adductor activity.

The decision to monitor EMG activity of two portions of the vastus medialis was based on anatomical evidence of differing fiber orientation and nerve supply to the inferior (VMO) and superior (VML) portions of that muscle.^{13,18,19} Subtle differences in the activity patterns of the VMO and VML, illustrated by the nonsignificant differences between VMO to VL and VML to VL ratios in Figure 5, are congruous with this anatomical differentiation. With respect to contributing to patellar alignment, however, the much greater obliquity of the fiber orientation of the VMO (40°–55° as compared with 15°–18° for the VML) indicates that the VMO plays a much greater role than the VML, which appears to be more closely aligned with the vastus intermedius in terms of both innervation and fiber orientation.¹⁹ As such, alterations in the VMO to VL ratio are much more likely to affect patellar tracking than comparable changes in the VML to VL ratio.

magnitude of resistance used in this study.

Comparison of normalized medial to lateral EMG ratios for the four exercises revealed no significant differences among the exercises in either the VMO to VL or VML to VL ratio. Though there are no previously published data with which these results may be directly compared, this study's findings are in agreement with anecdotal reports by Basmajian²⁵ and Wild and associates,²⁶ who stated that they had observed no change in the relative activity levels of the QF group when comparing SLR and SLR/LR exercises. Two other interesting trends may be noted in Figure 6. In contrast to the relatively low variability in the medial to lateral activity ratios associated with the QS exercise, all three variations of the SLR showed a relatively greater degree of variability across subjects. Although neither ratio showed statistically significant exercise effects, Figure 6 illustrates that the VMO and VML showed opposite trends, with the mean VMO to VL ratio actually being the lowest for the SLR/LR exercise, which has been advocated as a specific means of increasing VMO activity.

Our results do not appear to support the suggestion made by Hanten and Schulthies²³ that the VMO can be strengthened selectively by performing hip adduction exercises. This apparent discrepancy might be attributed to several differences in experimental protocol. Hanten and Schulthies' subjects were positioned with the knee in 60 degrees of flexion, and their subjects performed isometric hip adduction, which was resisted by a pad placed proximally to the knee. Their subjects apparently were not instructed to actively extend the knee, though the relatively high percentages of maximum QF EMG activity reported during the isolated hip adduction exercises (mean values of 61.75% for the VMO and 45.63% for the VL) would seem to indicate that subjects must have either generated significant knee extensor torques or co-activated the hamstring muscles along with the QF.

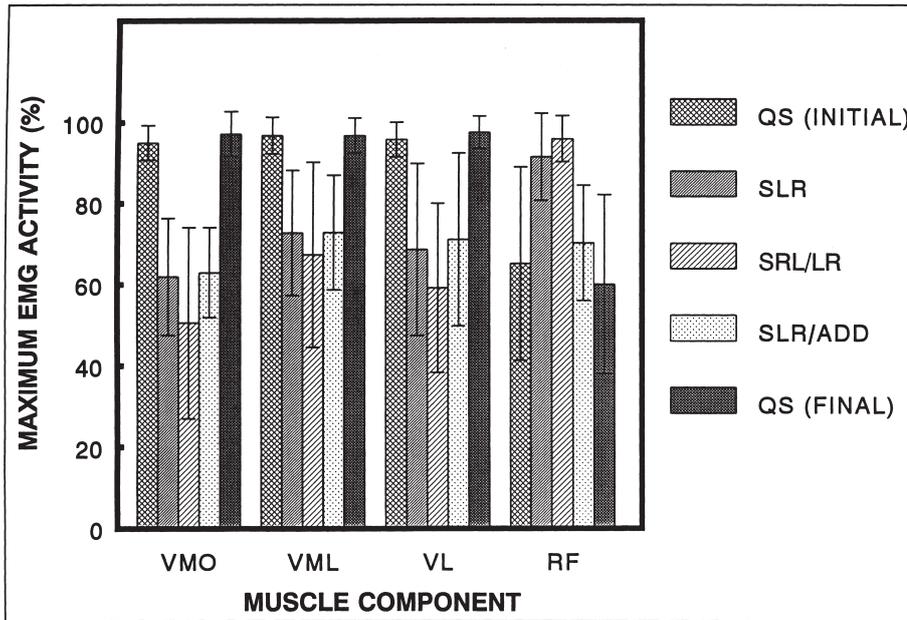


Figure 4. Percentage of maximum electromyographic (EMG) activity elicited by each of the exercises studied. Data for each muscle represent the mean (\pm SD) normalized EMG activity for all 12 subjects during the performance of initial and final quadriceps femoris muscle setting (QS) sets and three variations of the straight leg raising (SLR) exercise. For the single-joint extensors (VMO=vastus medialis obliquus, VML=vastus medialis longus, VL=vastus lateralis), both QS sets elicited significantly greater activity ($P < .05$) than any of the three SLR variations. The two-joint rectus femoris muscle (RF) exhibited nearly opposite behavior, with both the SLR and straight leg raising with hip laterally rotated (SLR/LR) exercises eliciting significantly greater activity than the QS and straight leg raising combined with isometric hip adduction (SLR/ADD) exercises ($P < .05$).

Comparison with Previous Findings

Our findings with respect to the maximum relative activity of the QF components across the exercises tested are summarized in Figure 6, in which data from the initial and final QS sets have been combined and the relative activity of each of the muscle groups is compared for each of the four exercises. Presenting the data in this manner emphasizes the marked difference in activity patterns between the single-joint knee extensors (VMO, VML, and VL) and the RF, which acts both to extend the knee and to flex the hip. All of the single-joint knee extensors tested demonstrated significantly greater mean activity during the QS exercise than during any of the SLR variations. The RF showed a nearly opposite pattern, demonstrating significantly greater activity during both the SLR and SLR/LR exercises than during the QS exercise.

These findings are in agreement with those of Soderberg and Cook³³ who compared vastus medialis and RF activity during QS and SLR exercises. These data support a distinct functional division between the one- and two-joint QF components. When the RF is strongly activated in order to exert a flexor torque at the hip, the single-joint knee extensors demonstrate submaximal activity (despite instructions to maintain a maximal QS throughout the SLR exercise), whereas the opposite is true during the performance of the isolated QS exercise. Because the single-joint QF components account for approximately 84% of the cross-sectional area of the QF,³⁴ this finding appears to have important clinical implications. Although the SLR is frequently considered to be a progression from the QS for QF strengthening, that assumption appears questionable for the single-joint QF components, at least for the

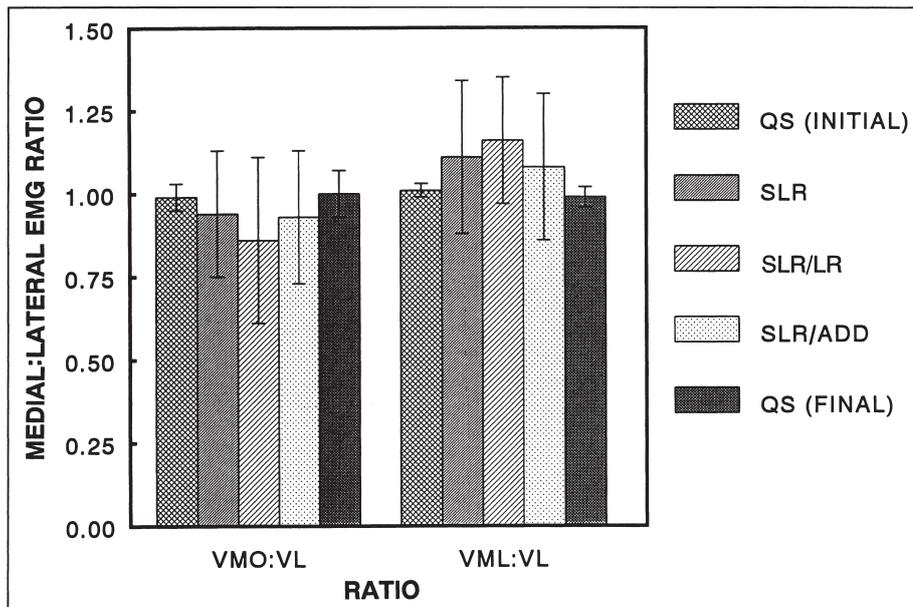


Figure 5. Medial to lateral ratios of normalized electromyographic (EMG) activity during each of the exercises studied. Data are mean (\pm SD) vastus medialis obliquus to vastus lateralis muscle (VMO:VL) and vastus medialis longus to vastus lateralis (VML:VL) activity ratios for all 12 subjects during the performance of initial and final quadriceps femoris muscle setting (QS) sets and three variations of the straight leg raising (SLR) exercise. There were no statistically significant differences across exercise conditions for either ratio. (SLR/LR=straight leg raising with hip laterally rotated; SLR/ADD=straight leg raising combined with isometric hip adduction.)

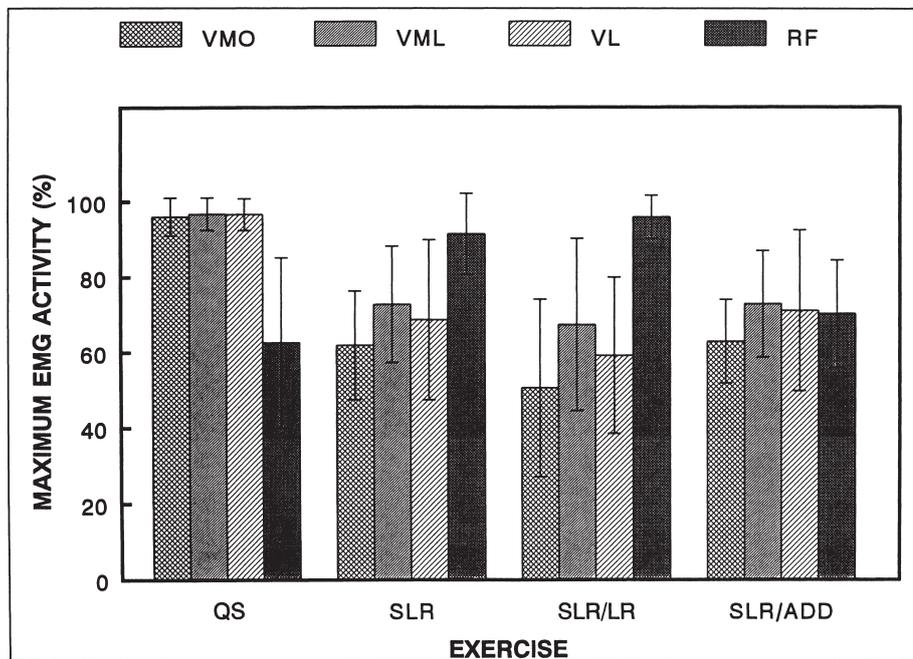


Figure 6. Percentage of maximum electromyographic (EMG) activity elicited by each of the exercises studied. Data for each exercise represent the mean (\pm SD) normalized EMG activity for all 12 subjects. Initial and final quadriceps femoris muscle setting (QS) sets have been combined. Note the similar pattern shown by all three single-joint knee extensors (VMO=vastus medialis obliquus, VML=vastus medialis lateralis, VL=vastus lateralis) and the marked contrast in the activity pattern of the two-joint rectus femoris muscle (RF).

Advocates of combining hip adduction with knee extension exercises have typically focused on the anatomical link between the VMO and the adductor magnus as the rationale for such exercises.^{14,22-24} An alternative rationale for hypothesizing an increase in the medial to lateral QF activity ratio during the performance of the SLR/LR and SLR/ADD exercises would be that muscle groups crossing the medial aspect of the knee joint (eg, the VMO and medial hamstrings) might be activated in response to stress of medial joint structures, such as the joint capsule and medial collateral ligament, in order to augment and protect those passive structures by providing dynamic support. The presence of sensory receptors in ligaments and the identification of ligamentous-muscular reflexes support this hypothesis.^{35,36} Although this possibility is intriguing, experimental results obtained while applying abduction torques to the human knee have provided little support for this hypothesis.

The most direct examination of this hypothesis in humans was performed by Andriacchi and colleagues,³⁷ who tested the effect of an external abduction torque applied at the knee during isometric knee extension at angles of 10, 20, and 40 degrees of flexion; no hip adduction torque was required of the subjects because the thigh was stabilized in their study. They reported that vastus medialis activity actually decreased when abduction torques were applied with the knee in 10 or 20 degrees of flexion, but increased slightly when the knee was flexed to 40 degrees. Their findings are further supported by the results obtained in our study, during which no increase in activation of the VMO was observed with the knee held in full extension, even though the lateral force applied at the ankle resulted in abduction torques at both the hip and knee.

Clinical Relevance of Findings

There is widespread agreement that conservative treatment of patients with patellofemoral joint dysfunction

should include active exercise aimed at strengthening the QF in general and the VMO in particular. In order to reduce the risk of exacerbating patellofemoral joint irritation, isometric QF exercises performed with the knee in full extension, such as the QS and SLR exercises used in this study, have been widely advocated. One of the questions addressed by this study is whether the likelihood of selectively strengthening the VMO is enhanced by modifying such exercises to elicit concurrent hip adductor muscle activity.

The results of our study do not support the suggestion that isometric QF strengthening exercises are more likely to preferentially activate the VMO when performed in conjunction with hip adductor activity. We found that one such exercise (ie, SLR/LR), which has been advocated for preferential strengthening of the VMO, actually elicited the lowest mean VMO to VL ratio of the four exercises studied. Moreover, performing the SLR/LR exercise with an ankle weight equal to 5% of body weight resulted in a mean VMO activity level of only 50.5% of the maximal activity that was typically attained during performance of the QS exercise. These findings suggest that, in cases requiring QF strengthening in the fully extended knee position, isometric QS may be the treatment of choice.

Limitations and Suggestions for Further Research

Because these results were obtained by studying subjects with asymptomatic knees, rather than patients with patellofemoral dysfunction, caution is warranted in extrapolating these findings to patient populations. It should be noted, however, that a recent study by Soderberg and Cook³³ of QF EMG activity during QS and SLR exercises demonstrated no significant differences between healthy subjects and patients with knee pathologies. Moreover, we would point out that the anatomical link between the VMO and the adductor magnus, which is the theoretical rationale presented by advocates of exercises such as the

SLR/LR, should be equally present in both healthy subjects and patients with patellofemoral dysfunction.

Other limitations of this study include the size of the sample and the magnitude of the external loads used. The results presented are based on a total of only 12 subjects (6 male, 6 female). Given the results of our pilot studies, the consistency of the findings across subjects, the identical findings for the male and female subgroups of the sample, and the general agreement with previous studies, we doubt that increasing the sample size would have altered the results. Future studies addressing this proposed functional link between the VMO and adductors could further address both the clinical relevance and reliability of these results by examining a larger sample that includes both healthy subjects and patients with knee pathology.

With respect to the loads studied, the decisions to use only a single level of external loading and to limit that level to 5% of body weight (for both the ankle weight and the laterally directed force) were based on the necessity of having all subjects complete the entire protocol of 25 QF exercises without fatiguing the QF group to a degree that would significantly alter the force/EMG relationship, the stability of which is critical to the validity of our conclusions. The 5% of body weight level was chosen on the basis of subjects' perception of the degree of effort required to complete the required tasks during pilot studies. Although the loads used for these healthy subjects were submaximal in all cases, subjects reported that the task of maintaining a strong QS set and consistent foot position throughout each of the exercises was not an easy task, and several subjects reported that the SLR exercise combined with adduction was quite difficult to perform at the load level used in this study. Furthermore, it is clear that the loads used in this study *were* sufficient to produce significant changes in the relative activity of the QF components, as evidenced by significant differences in activity of all QF components when comparing QS

and SLR variations and by a significant decrease in RF activity during the SLR/ADD exercise as compared with the other two variations of SLR. Whether greater loads would alter the medial to lateral QF activity ratio remains to be determined.

Although none of the exercises studied significantly increased the relative activity of the medial QF components to a greater degree than the lateral components, the rationale for preferential strengthening of the VMO in patients with patellofemoral dysfunction appears sound. The methodology used in this study could be adapted to examine patterns of QF activity in terms of both timing and magnitude of EMG activity in medial and lateral QF components during various rehabilitation protocols and in relation to functional activities. Of particular relevance to the treatment of patellofemoral dysfunction is the manner in which other currently advocated therapeutic interventions, such as patellar taping or the use of weight-bearing exercises, might affect medial to lateral QF activity ratios. It is important to note, however, that the validity of studies using EMG data to infer the relative effectiveness of various strengthening protocols depends on careful design and implementation, particularly with respect to EMG processing and normalization procedures and the limitations of the force-EMG relationship.

Conclusions

The results suggest that exercises requiring combined hip adduction and knee extension torques, such as SLR/LR or SLR/ADD exercises, are not superior to the QS or the standard SLR exercise in eliciting an increase in the relative activity of the medial components of the QF. Our results also support and expand upon previous studies indicating that QS exercises tend to elicit a greater degree of activity of the single-joint knee extensors than do SLR exercises. These results suggest that for patients needing an increased medial to lateral force ratio acting on the patella in addition to generalized QF strength-

ening, isometric QS exercises may actually be more beneficial than SLR/LR or SLR/ADD exercises.

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Commentary

There is a need in physical therapy to evaluate common rehabilitation practices, so it can be determined whether the desired outcome of a particular therapeutic procedure has been achieved. It is only after this sort of scrutiny that we will grow as a profession. The authors are to be commended for pursuing this aim. They have investigated the common clinical claim that particular modification of the straight-leg-raising (SLR)

exercise causes preferential activation of the vastus medialis obliquus muscle (VMO). Specific activation of the VMO has been advocated for patients with patellofemoral pain to improve patellofemoral tracking. It must be questioned, however, whether this report adds much to our body of knowledge, as similar research was performed by Soderberg and colleagues.^{1,2} The difference with this study is that the authors have exam-

ined the effect of a lateral rotation component, as well as an adduction component, to the SLR maneuver. The rationale for this addition was that exercises combining activity of the hip adductors in conjunction with conventional knee extensor strengthening activities such as the SLR have been advocated as a means of preferentially activating and exercising the VMO.

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Quadriceps Femoris Muscle Components**

Gregory M Karst and Paul D Jewett
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