Vastus Medialis Activation During Knee Extension Exercises: Evidence for Exercise Prescription

Lori A. Bolgla, Scott W. Shaffer, and Terry R. Malone

Context: Knee extension exercise is an important part of knee rehabilitation. Clinicians prescribe non-weight bearing exercise initially and progress patients to weight bearing exercise once they can perform a straight leg raise (SLR).

Objective: Compare VM activation during a SLR and weight bearing exercises.

Design: One-way repeated measures design. Setting: University Laboratory.


Results: The SLR had greater activation than the single leg stance and bilateral squat exercises. The step-up and unilateral leg press exercises had the greatest activation.

Conclusions: SLR performance can be an important indicator for exercise progression. These results provide foundational knowledge to assist clinicians with exercise prescription.

Quadriceps weakness, specifically of the vastus medialis (VM), is a common impairment following a knee injury or surgical intervention. Such weakness can have a significant impact functionally because many activities of daily living (ADLs), like walking, squatting, and stair climbing, require adequate quadriceps strength. Therefore, clinicians typically develop and implement interventions that focus on restoring VM strength to facilitate improved function as rapidly as possible.1-5

VM weakness may result from either muscle atrophy or neuromuscular inhibition. Recently, Mizner et al6 reported that failure of voluntary contraction (neuromuscular inhibition), not loss of muscle cross-section area (atrophy), accounted for quadriceps weakness in patients following total knee arthroplasty. Based on this finding, therapeutic exercises that facilitate VM activation may be more beneficial for patients following knee injury or surgery.7

Electromyography (EMG) is a commonly used tool capable of providing information regarding muscle activation during rehabilitation exercises. Researchers8-17 have examined VM activity during various non-weight bearing and weight bearing exercises and have hypothesized that when appropriately sequenced, exercises that generate higher activation may benefit patients with knee pathology.
A challenge facing clinicians is the implementation of a progressive yet safe knee extension exercise program. Weight bearing exercises are important because they incorporate demands required to perform many ADLs; however, patients initially lack adequate quadriceps activation to safely perform weight bearing exercise. Therefore, rehabilitation professionals typically prescribe non-weight bearing exercises, like isometric quadriceps contractions and straight leg raises (SLR). Greenfield has stated that “Clinical experience indicates that after the patient eliminates an extensor lag and soft tissue healing is complete, safe independent weight bearing can commence. The ability to adequately perform a SLR has been used as a clinical indicator for initiating weight bearing activities and represents a significant marker for progressing to weight bearing activities.”

To our knowledge, researchers have not directly compared VM activation during a SLR exercise to activation during a progression of weight bearing exercises. Comparison of activation generated during a SLR to that during more functional, weight bearing exercises will assist clinicians with exercise prescription. We hypothesize that greater VM activity will be generated during a SLR compared to an initial weight bearing activity, like single leg stance; therefore, patients who can adequately perform a SLR should then demonstrate the ability to generate sufficient quadriceps activity needed to safely initiate weight bearing exercise.

The purpose of this study was two-fold. The primary purpose was to compare VM activation during a SLR to 6 commonly prescribed weight bearing knee extension exercises. A secondary purpose was to determine the relative activation among a sequence of weight bearing knee extension exercises. We believe that results from this study will provide additional evidence to delineate appropriate use and sequencing in knee rehabilitation.

**Methods**

**Research Design**

This study used a 1-way repeated measures design. The independent variable was the knee extension exercise (SLR exercise and 6 weight bearing knee extension exercises). The dependent measure was VM activation amplitudes, expressed as a percent of a maximum voluntary isometric contraction, during the knee extension exercises.

**Subjects**

Eight female (age = 22.2 ± 2.9 years, height = 1.7 ± 0.1 m, mass = 60.4 ± 6.9 kg) and 7 male (age = 24.5 ± 3.2 years, height = 1.8 ± 0.2 m, mass = 88.6 ± 7.2 kg) healthy subjects volunteered for this study. A sample of convenience was recruited from the local university community, and inclusion criteria required that all participants safely perform a single leg stance on each lower extremity with the knee maintained in a fully extended position (ie, no evidence of a knee flexion contracture). Subjects were excluded if they had a history of a significant lower extremity injury or surgery in the previous year. The primary investigator explained the risks and benefits involved with the study, and all subjects signed an informed consent approved by the University of Kentucky Institutional Review Board. All procedures followed
were in accordance with the ethical standards of the University of Kentucky Institutional Review Board.

Rehabilitation Exercises

The SLR exercise was used as a reference for comparing muscle activation between non-weight bearing and weight bearing knee extension exercises. We chose 6 weight bearing exercises representative of a continuum of those routinely used in clinical settings. The 2 single leg stance tasks (one in full knee extension and one with the knee flexed to 30 degrees) were used because they represent initial weight bearing activities. As a transition toward more demanding weight bearing exercises, we used a bilateral squat with the knees flexed to 60 degrees. The next sequence was a step-up onto (step-up) and step-down from (step-down) a 20-cm high step because these exercises assess dynamic concentric and eccentric control, respectively. The final exercise was a unilateral leg press (load equal to 33% of body weight with the knee flexed to 80 degrees). This exercise differed because it required muscle activation in lower portions of knee flexion. Table 1 provides a detailed description of each exercise.

Procedures

Subjects reported to the Musculoskeletal Laboratory for a single testing session. All reviewed and signed an informed consent prior to data collection. The principal investigator then instructed subjects on the proper technique for each exercise (see Table 1). Subjects practiced each exercise to become familiar with each task and rested 5 minutes prior to testing to reduce the possible effect of fatigue. The principal investigator monitored these warm-up activities.

Subjects’ skin was prepared for EMG instrumentation by shaving, abrading, and cleansing it with isopropyl alcohol prior to application of surface electrodes. Bi-polar Ag-AgCl surface electrodes (Medicotest, Rolling Meadows, IL), measuring 5 mm in diameter with an interelectrode distance of approximately 20 mm, were placed in parallel arrangement over the muscle belly of the VM. The VM electrodes were placed approximately 4 cm superior and 3 cm medial to the superomedial border of the patella and oriented 55° to the vertical. Electrodes were further secured to the skin with an adhesive tape to prevent slippage during testing. A ground electrode was placed on the ipsilateral tibial tubercle. Electrode placements were visually confirmed on an oscilloscope using manual muscle testing techniques. A 3-second standing “quiet” file was also recorded to exclude ambient noise.

Next, the subjects performed 3 maximum voluntary isometric contractions (MVIC) for the VM to enable normalization of the raw EMG data. For this purpose, subjects pushed against a dynamometer with the knee placed in 80 degrees of flexion. Subjects produced a maximal isometric contraction using the “make” test to the beat of a metronome set at 60 beats per minute. They generated maximum force over a 2-second period and maintained this force for an additional 5 seconds to the beat of the metronome. Subjects performed one practice and 3 test trials, with a 30-second rest period between trials.

A computer algorithm determined the maximum root mean squared (RMS) amplitude recorded over a moving 500 millisecond (ms) average window across
<table>
<thead>
<tr>
<th><strong>Activity</strong></th>
<th><strong>Description</strong></th>
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<tr>
<td>Unilateral leg press</td>
<td>A weight equal to 33% of the subjects’ body weight was configured on the leg press machine. Subjects were positioned on the leg press machine with the knees flexed to 80 degrees and the feet in a neutral position. Then, they solely bore the weight equal to 33% body weight on the right lower extremity for a 5-second period and performed 3 repetitions of this exercise. Subjects were positioned so that the knee did not go past the toes.</td>
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<td>Step-up onto 20-cm high box</td>
<td>Subjects began this exercise standing in front of the box with the feet flat on the ground facing the box and both knees in an extended position. Subjects stepped onto and off of a 20-cm high box leading with the right lower extremity at a rate of 60 beats per minute. They were instructed not to raise the heel of the opposite foot to assist with lifting the body onto the box. They performed 9 repetitions of this exercise. EMG activity from the concentric portion of the task was used for data analysis.</td>
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<tr>
<td>Step-down from 20-cm box</td>
<td>Subjects began this exercise standing on top of the box with both feet facing forward and flat on the box and both knees in an extended position. They stepped off of and onto a 20-cm high box leading with the right lower extremity at a rate of 60 beat per minute. They performed 9 repetitions of this exercise. EMG activity from the eccentric portion of the task was used for data analysis.</td>
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<td>Isometric quadriceps contraction with straight leg raise</td>
<td>Subjects were positioned supine on a plinth with the right knee fully extended, the right ankle dorsiflexed in a neutral position, and the left knee flexed to 60 degrees. To the beat of a metronome set at 60 beats per minute, they performed an isometric quadriceps contraction on the first beat, lifted the right lower extremity to the level of the opposite knee on the second beat, and returned the right lower extremity to the plinth on the third beat. Subjects performed 9 repetitions of this exercises.</td>
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<td>Bilateral squat</td>
<td>Subjects stood with the lower extremities shoulder width apart and weight equally distributed. They were then positioned in 60 degrees of knee flexion bilaterally in a manner in which the knees did not move in front of the toes. They held this position for a 5-second period and performed 3 repetitions of this exercise.</td>
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<td>Single leg stance at 30 degrees knee flexion</td>
<td>Subjects performed a single leg stance on the right lower extremity with the knee in 30 degrees of flexion and the hip and foot in a neutral position (ie, forward tibial displacement over a neutral foot). They held this position for a 5-second period and performed 3 repetitions of this exercise.</td>
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<td>Single leg stance with full knee extension</td>
<td>Subjects performed a single leg stance on the right lower extremity with the knee in full extension and the foot in a neutral position. They held this position for a 5-second period and performed 3 repetitions of this exercise.</td>
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the three MVICs. The window of activity having the greatest amplitude was identified and this amount was assumed to represent 100% of the maximum voluntary isometric contraction (% MVIC) for the VM. All data were expressed as a percent MVIC for statistical analysis.

For testing purposes, subjects performed each exercise as described in Table 1. They rested 1 minute between each exercise, and we randomized testing order to reduce fatigue and ordering bias.

**EMG Analysis**

A 16-channel EMG system (Run Technologies, Mission Viejo, CA) recorded the VM muscle activity. Subjects wore a Myopac transmitter belt unit (Run Technologies) that transmitted all raw EMG data at 1000 Hz via a fiber optic cable to its receiver unit. Unit specifications for the Myopac included a common mode rejection ratio of 90 dB and an amplifier gain of 2000 for the surface EMG electrodes. Raw EMG data were band pass filtered at 20 to 500 Hz using Datapac software (Run Technologies), stored on a PC computer, and analyzed using Datapac software.

For each exercise, we then calculated the RMS amplitude for each repetition and expressed these amounts as a percent MVIC. For the single leg stance (at 0 and 30 degrees knee flexion), leg press, and bilateral squat exercises, we determined the amplitude during the middle 3 seconds of each repetition. For the SLR exercise, we determined the amplitude for the middle 5 repetitions of this activity. For the step-up and step-down exercises, we only analyzed activity from the concentric and eccentric portions, respectively, and determined the amplitude for the middle 5 repetitions of each task. Normalized data for each exercise were then averaged and used for statistical analysis.

**Statistical Analysis**

A 1-way analysis of variance (ANOVA) with repeated measures was used to determine differences in VM activation amplitudes among exercise conditions. Significant differences between exercises were determined using the sequentially rejective Bonferroni (Bonferroni-Holm) test. Statistical analysis was performed using SPSS Version 12.0 (SPSS Inc, Chicago, IL). Statistical significance was established at the 0.05 level.

**Results**

Table 2 summarizes the descriptive statistics for normalized EMG activity under each exercise condition. The 1-way ANOVA with repeated measures indicated a significant main effect across exercise ($P < .001$). Post hoc analysis revealed that the unilateral leg press and step-up generated the greatest VM activity with values significantly different ($P < .005$) from the bilateral squat and single leg stance at 0 and 30 degrees of knee flexion. The step-down, SLR, bilateral squat, and single leg stance at 30 degrees of knee flexion had significantly greater VM activation ($P < .005$) than the single leg stance at 0 degrees knee flexion.
The primary purpose was to compare VM activation during a SLR to 6 commonly prescribed weight bearing knee extension exercises. We initially hypothesized that the SLR exercise would generate greater VM activation than some weight bearing exercises used early in the rehabilitation process. During the SLR exercise, our subjects generated average VM activity equal to 26% MVIC. VM activity during the weight bearing exercises ranged from 6% (single leg stance at 0 degrees knee flexion) to 41% MVIC (unilateral leg-press). These findings suggest that clinicians may use the ability to adequately perform a SLR as a clinical indicator for initiating weight bearing activities. A secondary purpose was to determine the relative activation among a sequence of weight bearing knee extension exercises. Our findings showed an increase in VM activity relative to increased task complexity. Clinicians may use this information to delineate appropriate use and sequencing of weight bearing exercises over the course of rehabilitation.

### Table 2  Means ± Standard Deviation for Vastus Medialis Electromyographic Amplitudes During Each Exercise Expressed as a Percent of a Maximum Voluntary Isometric Contraction (% MVIC) for 7 Knee Extension Exercises

<table>
<thead>
<tr>
<th>Exercise</th>
<th>% MVIC</th>
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<tr>
<td>1. Unilateral leg press*</td>
<td>41 ± 19</td>
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<tr>
<td>2. Step-up onto 20-cm high box*</td>
<td>32 ± 15</td>
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<tr>
<td>3. Step-down from 20-cm high box†</td>
<td>27 ± 12</td>
</tr>
<tr>
<td>4. Isometric quadriceps contraction with straight leg raise†</td>
<td>26 ± 14</td>
</tr>
<tr>
<td>5. Bilateral squat†</td>
<td>18 ± 8</td>
</tr>
<tr>
<td>6. Single leg stance at 30 degrees knee flexion†</td>
<td>16 ± 7</td>
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<tr>
<td>7. Single leg stance with full knee extension</td>
<td>6 ± 3</td>
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</table>

* Exercises 1 and 2 significantly greater than exercises 5 through 7 (P < .005). † Exercises 3 through 6 significantly greater than exercise 7 (P < .005).

**Comments**

The primary purpose was to compare VM activation during a SLR to 6 commonly prescribed weight bearing knee extension exercises. We initially hypothesized that the SLR exercise would generate greater VM activation than some weight bearing exercises used early in the rehabilitation process. During the SLR exercise, our subjects generated average VM activity equal to 26% MVIC. VM activity during the weight bearing exercises ranged from 6% (single leg stance at 0 degrees knee flexion) to 41% MVIC (unilateral leg-press). These findings suggest that clinicians may use the ability to adequately perform a SLR as a clinical indicator for initiating weight bearing activities. A secondary purpose was to determine the relative activation among a sequence of weight bearing knee extension exercises. Our findings showed an increase in VM activity relative to increased task complexity. Clinicians may use this information to delineate appropriate use and sequencing of weight bearing exercises over the course of rehabilitation.

**VM Activation During Non-Weight Bearing and Weight Bearing Exercise**

The SLR exercise generated greater activity compared to less demanding weight bearing knee extension exercises. One reason for this finding was that subjects began the SLR by first performing an isometric quadriceps contraction. Soderberg et al. reported that an isometric quadriceps contraction in combination with a SLR resulted in significantly greater VM activity than an isolated SLR.

VM activation during the SLR exceeded that generated during both single leg stance activities. These findings are clinically relevant because patients can perform a SLR in a protected (non-weight bearing) and safe (no resultant injury from non-performance) manner early in the rehabilitation process. It also provides information regarding the patient’s ability to generate VM activity required to perform initial weight bearing activities. The ability to adequately perform a SLR may serve as
an indicator of function without risking injury associated with weight bearing; however, additional studies are needed to make this determination.

**Weight Bearing Exercise Progression**

Our findings indicated that the weight bearing exercises required varying levels of VM activation. The single leg stance, with full knee extension, required the least amount of VM activity. For this exercise, subjects were positioned with the femur congruent with the tibia and their center of mass over the stance leg (see Figure 1). Together, these factors most likely placed the knee in a more stable position, thus minimizing VM activity. The single leg stance, with the knee flexed to 30 degrees, represented a more demanding task. In this case, knee flexion increased the applied torque due to gravity (Figure 1), resulting in greater VM activation. More clinically relevant was that both exercises generated less VM activation compared to the SLR.

**Figure 1** — This figure illustrates the applied torque due to gravity onto the quadriceps during single leg stance with the knee fully extended and placed in 30 degrees of flexion. The vertical, solid line shows the force due to gravity. The horizontal, broken line represents the length of the external moment arm (perpendicular distance of the force due to gravity from the center of the knee joint) in each position. The external moment arm in the Figure on the left (A) is negligible because the subject’s center of mass is positioned over the knee joint. The external moment arm in the Figure on the right (B) is relatively greater because the subject’s center of mass is positioned posterior to the knee joint. This position created a greater knee flexion moment and required subjects to generate greater vastus medialis electromyographic activity to counteract the knee flexion moment.
and the other weight bearing exercises. Based on these findings, these single leg stance exercises appear to be appropriate initial weight bearing activities.

The bilateral squat required VM activity similar to the single leg stance with the knee flexed to 30 degrees. Although the bilateral squat incorporated double limb support, it had a relatively greater applied torque due to gravity because the subjects performed the squat in 60 degrees of knee flexion. During the bilateral squat, subjects generated an average VM activity equal to 18% MVIC, which was comparable to values reported by Coqueiro et al\textsuperscript{14} during a similar activity. Findings from the Coqueiro study and the current one inferred that the bilateral squat exercise can be an appropriate manner to initially apply greater loads onto the quadriceps. Since ADLs like squatting and stair climbing require VM activation with greater knee flexion, these findings support the use of the bilateral squat as a safe transition toward these activities.

The step-down and step-up exercises generated the next greatest VM activity and differed because of their dynamic nature. During the step-down exercise, subjects lowered their body in a controlled manner by eccentrically contracting the quadriceps. This motion required greater VM activity compared to the bilateral squat because subjects had to control the excursion of the body’s center of mass over a single lower extremity. Also, performance of the step-down and step-up exercises might have resulted in greater displacement of the tibia over the foot. This motion most likely shifted the subject’s center of mass in a posteriorly-directed position. Such displacement would require greater EMG activity to counterbalance the increased torque due to gravity. We cannot unequivocally make this determination, however, since kinematics was not assessed. Finally, though not significantly different, the step-up generated greater VM activity than the step-down. Researchers\textsuperscript{8,27} have compared eccentric and concentric muscle activity and consistently reported greater EMG amplitudes during concentric actions. Based on these findings, clinicians may first introduce the step-down exercise prior to the step-up.

The unilateral leg press required the greatest VM activity. Although subjects were seated during this exercise, they performed this exercise with the knee flexed to 80 degrees. Greater knee flexion elongated the quadriceps, which would affect the muscle’s length-tension relationship. Placing the quadriceps in a position of less than optimal length-tension relationship (less cross-bridge overlap) most likely accounted for greater VM activation.\textsuperscript{21} This finding supports, therefore, the clinician’s decision to introduce higher demanding quadriceps exercises with the knee positioned in greater flexion later in the rehabilitation process.

**Limitations**

The present study has limitations that we would like to address. First, it included a cohort of young, healthy adults that precludes direct extrapolation of our findings to patients with knee pathology. This also potentially limits these findings to patients who have co-morbidities or age-related decline that result in diverse impairments (eg, pain and weakness) and functional limitations. Second, only the unilateral leg press exercise reached a level to stimulate consistent muscle strength adaptations as expected in normal subjects; therefore, our program may enhance neural adaptation and motor relearning of basic functional tasks, but not provide the intensity needed to induce large shifts in muscle strength or high level activities.
Future Research

Additional studies involving larger samples of age and disease-specific cohorts are warranted and may assist in further defining the patient populations that may benefit from the exercises included in this study. Future research should also include a larger spectrum of resistance exercise and reliable and valid measures that link EMG analysis to functional outcomes. Finally, researchers should determine the relative activation between the VM and other quadriceps muscles during these exercises.

Conclusion

This study identified the relative activation of the VM during 7 commonly prescribed knee extension exercises. These results provide additional foundational knowledge to assist clinicians in the development and refinement of exercise progression, especially in the early portions of rehabilitation following injury or surgery. In particular, the straight leg raise exercise produced levels of neuromuscular activation that exceeded those obtained during 2 single leg stance and a bilateral squat exercise. The clinical benefit and utility of the data suggest using the SLR as the initial marker of function required for the safe introduction of other weight bearing lower extremity exercises.

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References


