J Appl Physiol 124: 1438–1446, 2018.
First published February 8, 2018; doi:10.1152/japplphysiol.00702.2017.

RESEARCH ARTICLE

Hip position and sex differences in motor unit firing patterns of the vastus medialis and vastus medialis oblique in healthy individuals

Yi-Ling Peng,[1] Matthew S. Tenan,[2] and Lisa Griffin[1]

[1]*Department of Kinesiology, University of Texas at Austin, Austin, Texas; and* [2]*Human Research & Engineering Directorate, U.S. Army Research Laboratory, Aberdeen Proving Ground, Maryland*

Submitted 2 August 2017; accepted in final form 31 January 2018

Peng YL, Tenan MS, Griffin L. Hip position and sex differences in motor unit firing patterns of the vastus medialis and vastus medialis oblique in healthy individuals. *J Appl Physiol* 124: 1438–1446, 2018. First published February 8, 2018; doi:10.1152/japplphysiol.00702.2017.—Weakness of the vastus medialis oblique (VMO) has been proposed to explain the high prevalence of knee pain in female subjects. Clinicians commonly use exercises in an attempt to preferentially activate the VMO. Recently, our group found evidence to support clinical theory that the VMO is neurologically distinct from the vastus medialis (VM). However, the ability to voluntarily activate these muscle subsections is still disputed. The aim of this study was to determine if VM and VMO activation varies between sexes and if control of the two muscles is different between rehabilitation exercises. Thirteen men and 13 women performed isometric straight leg raises in two hip positions, neutral hip rotation and 30 degrees lateral hip rotation. Bipolar intramuscular fine-wire electrodes were inserted into the VM and VMO to obtain motor unit recruitment thresholds and initial firing rates at recruitment. Linear mixed models and Tukey post hoc tests were used to assess significant differences in 654 motor units. Women demonstrated faster motor unit firing rate at recruitment, 1.18 ± 0.56 Hz higher than men. Motor units fired 0.47 ± 0.19 Hz faster during neutral hip rotation compared with lateral hip rotation. The VMO motor units were recruited 2.92 ± 1.28% earlier than the VM. All motor units were recruited 3.74 ± 1.27% earlier during neutral hip rotation than lateral hip rotation. Thus the VM and the VMO can be activated differentially, and their motor unit recruitment properties are affected by sex and hip position.

NEW & NOTEWORTHY This is the first study to reveal differential activation of the vastus medialis oblique from the vastus medialis in clinical exercise protocols. Our research group used fine-wire electrodes to examine EMG signals of the vastus medialis oblique and vastus medialis to avoid possible cross talk. We also consider the effect of sex on motor unit firing patterns because of higher prevalence of knee pain in women, and yet few studies evaluating the sex differences in neuromuscular control.

fine-wire recording; intramuscular EMG; knee; leg position; quadriceps

INTRODUCTION

There is a long-held belief among physical medicine clinicians that the vastus medialis oblique (VMO) and vastus medialis (VM) are anatomically and neurologically distinct (11, 46). Although early surface electromyography (EMG) research disputed this clinical ideology (39, 44), our research group recently demonstrated differential discharge patterns between the VM and VMO (48, 50). Furthermore, Gallina et al. (18) demonstrated regional muscle activation induced by electrical stimulation in the vastus medialis complex. They found that the proximal portion of the VM could be activated separately from the distal portion in an isometric knee extension task and that the distribution of the localized activation was influenced by knee flexion angle (18). Anatomical studies on human cadavers report that the VMO is innervated by a larger number of terminal nerve branches originating from L1–L3 per area than the VM (23, 51). These findings support the notion that the VM and VMO can be controlled independently.

Anatomical evidence also suggests that there is a functional difference between the VM and VMO based upon dissimilar muscle fiber pennation angles (14). The VMO runs oblique to the medial side of the patella and assists with medial patellar translation, whereas the VM runs more longitudinally and contributes to knee extension (3). An advanced and adequate medial force generated by the VMO not only decreases patellofemoral joint load but also reduces the lateral dominant forces from the vastus lateralis (VL) (33). An imbalance of muscle forces between the medial and lateral sides of the patella, caused by VMO weakness or activation delay, is considered to be a primary contributing factor to patellofemoral pain syndrome (PFPS) (29).

Female subjects are more likely to experience PFPS and knee injury than male subjects (4, 16, 47). A plausible explanation may be due to sex differences in the activation patterns of the VMO in relation to the VL (6). If the VMO is too weak to counteract the excessive force of the VL, pain can result from mal-tracking of the patella (35). A lower medial to lateral quadriceps activation ratio is evident in healthy female subjects compared with healthy male subjects (32). However, not all EMG studies support the notion that higher incidence of PFPS in female populations is a result of differential VMO/VL intensity (6, 21). The discrepancy in the results may be related to the inconsistent surface EMG electrode placements (21). This is especially true for the electrode location of the VMO, which is sometimes not specified and confused with the VM (32).

Clinical assessments and rehabilitation protocols commonly assume VMO weakness. Some studies have found that the relative activation amplitude and onset timing of the VMO to the VL can be affected by different exercises (15), eccentric vs. concentric contractions (21), tibia rotation (26, 41), and hip adduction (13, 26). Conversely, others have not observed

Address for reprint requests and other correspondence: L. Griffin, Dept. of Kinesiology and Health Education, Belmont Hall, D3700, Univ. of Texas at Austin, Austin, TX (e-mail: l.griffin@austin.utexas.edu).

differences in the relative activation of the VMO and VL across exercise type (21), hip rotation (21), or hip adduction (36). It is possible that much of the research on quadriceps activity to date were confounded by cross talk with the use of surface EMG since the standard surface electrodes lack the ability to reliably detect VMO activity apart from other adjacent muscles due to signal cross talk (8). The use of fine-wire EMG recording can overcome the problem of cross talk between recordings of muscles in close proximity.

The straight leg raise (SLR) is an exercise commonly prescribed by clinicians to strengthen the quadriceps in general and, in particular, the VMO (45). The SLR is beneficial for people with general knee pain or after knee surgery because it induces minimal compression force on the patellofemoral joint (28, 43). Some researchers have suggested that simultaneous activation of the hip adductor and quadriceps muscles preferentially recruits the VMO (19, 22). Since the VMO muscle fibers arise mainly from the adductor magnus tendon (5), concurrent contraction of the hip adductor may provide a stable origin for the VMO and facilitate its neuromuscular activation (19). Using surface EMG, Sykes and Wong (45) found that the SLR with lateral hip rotation was the most effective position for strengthening the VMO. However, they noted that the higher EMG amplitudes of the VMO during hip lateral rotation could have been due to cross talk from the hip adductors (45). Conversely, Karst and Jewett (24) found that SLR with lateral hip rotation actually elicited a lower mean VMO/VL EMG ratio compared with standard SLR without hip rotation. During various exercises, such as isometric quadriceps setting exercise, end range knee extension, and squatting, VMO recruitment was not facilitated by concurrent hip lateral rotation or hip adduction, even with increased adductor magnus activation (10, 55). Thus the ambiguous surface EMG literature suggests a need for more specific intramuscular fine-wire EMG investigations to evaluate vastus medialis complex activity during the SLR.

The purpose of this study is to evaluate muscle activation patterns during the SLR in two hip rotation positions and to determine if one position facilitates preferential motor unit recruitment of the VMO compared with the VM. With methodological control of the female menstrual phase, the study also examines if sex can account for differences in performance of the two muscles.

METHODS

Participants and ethical approval. Thirteen young men (26.1 ± 3.7 yr) and 13 young eumenorrheic women (26.5 ± 4.3 yr) participated in one study visit. The inclusion criteria for both men and women were absence of ongoing hip, knee, or ankle pain, previous leg surgery, immobilization, arthritis to the dominant leg, and neurologic, cardiovascular, or metabolic disorders. In addition, the female participants had regular menstrual cycles for the 3 mo before the experiment. The women participated during their late follicular phase (for example, *day 8* to *day 14* in a 28-day menstrual cycle), because single motor unit firing rates and recruitment thresholds in women are comparable with those of men during this phase (50). All participants signed an informed consent form and all experimental procedures were approved by the University of Texas at Austin Institutional Review Board.

Experimental protocol. All data collection procedures were conducted in the Neuromuscular Physiology Laboratory at the University of Texas at Austin. All participants were instructed to avoid strenuous exercise 48 h before the study visit and refrain from consuming caffeine and alcohol for 8 h before testing. Participants were seated in an adjustable chair for fine-wire EMG electrode placement in the dominant leg. Two pairs of bipolar intramuscular insulated stainless steel fine-wire electrodes (0.002 mm, California Fine Wire, Grover Beach, CA) with 3 mm of insulation removed from the tip were inserted into the VMO and VM with thin (25 gauge, 16-mm length), disposable hypodermic needles. Signals obtained from the wires were preamplified and bandpass filtered at 8 Hz–3.12 kHz with a gain of 330 (B&L Engineering, Tustin, CA). All electrodes and needles were fully autoclaved and sterilized before use. The two fine-wire electrodes for the VMO were placed at 4 and 5 cm proximal to the superomedial border of the patella and oriented 55° medially from the femoral axis. The two electrodes for the VM were placed at 11 and 12 cm proximal to the superomedial border of the patella and oriented 15° medially from the femoral axis (40, 52). An adhesive pregelled Ag/AgCl surface electrode of 5-mm diameter was placed on the ipsilateral patella as a ground.

After electrode placement, the volunteer was positioned lying supine on a medical examination table with the legs straight. The upper trunk, waist, and nondominant thigh were immobilized with straps and the dominant ankle was affixed to a padded restraint attached to a strain gauge (Entran Sensor & Electronics, Fairfield, NJ) underneath the table. An isometric SLR was performed in two different hip positions: neutral (no rotation) and 30° of lateral hip rotation. The foot was securely positioned between two boards to maintain the required hip rotation and neutral foot position during the contraction. The instruction for the movement was to "lift your leg straight up with your knee fully extended." The participants were guided to perform three, 3-s isometric maximal voluntary contractions (MVCs) with a 1-min rest between contractions to prevent muscle fatigue. MVCs were performed until three equivalent MVC values were obtained. The intraclass correlation coefficient [ICC(3,1)] for the MVCs was 0.99. The average of the three MVCs were used to determine submaximal contraction target levels.

Following the MVCs, the participants practiced a slowly controlled ramp contraction following a line on a computer screen in front of them with a rate of rise of 7.5% MVC/s up to 75% MVC and then a hold at 75% MVC for 5 s. One successful trial ramp with smooth force generation for each hip position was recorded. Thus a total of two ramp contractions were recorded and analyzed for each participant. Intramuscular EMG and force data were recorded in Spike2 (version 5.21, Cambridge Electronic Design, Cambridge, UK) with sampling rate at 30 kHz and 1 Hz, respectively.

Motor unit and force data analysis. The intramuscular EMG data was bandpass filtered at 100–8,000 Hz using a fourth-order recursive Butterworth filter in Matlab (version 2010b, Mathworks, Natick, MA). Single motor units were analyzed visually and identified based upon individual shape, amplitude, and discharge frequency in Spike2. The recruitment threshold and initial firing rate at recruitment for each individual motor unit were analyzed. Recruitment threshold for each motor unit was defined as the force of the first spike of four consecutive spikes normalized to MVC (50, 54). Initial firing rate at recruitment was calculated as the average of the first three interspike intervals converted into hertz (Fig. 1). The force data was notch filtered at 60 Hz using a fourth-order recursive Butterworth filter in Matlab (version 2010b, Mathworks) and the DC offset was removed.

Statistical analysis. All statistical analysis was performed in R, using RStudio (version 3.2.2) (38), using the lmerTest (25), lme4 (2), and nlme (37) packages. The α level of significance was set a priori at $P < 0.05$. Linear mixed models with an unstructured variance covariance structure and Tukey post hoc tests were used to evaluate the effect of muscle (VM and VMO), sex (male and female), and hip position (no hip rotation and 30 hip lateral rotation) on initial firing rate and recruitment threshold during the SLR. Mixed effects models were used because multiple motor units from an individual are statistically correlated (49) and mixed models account for this corre-

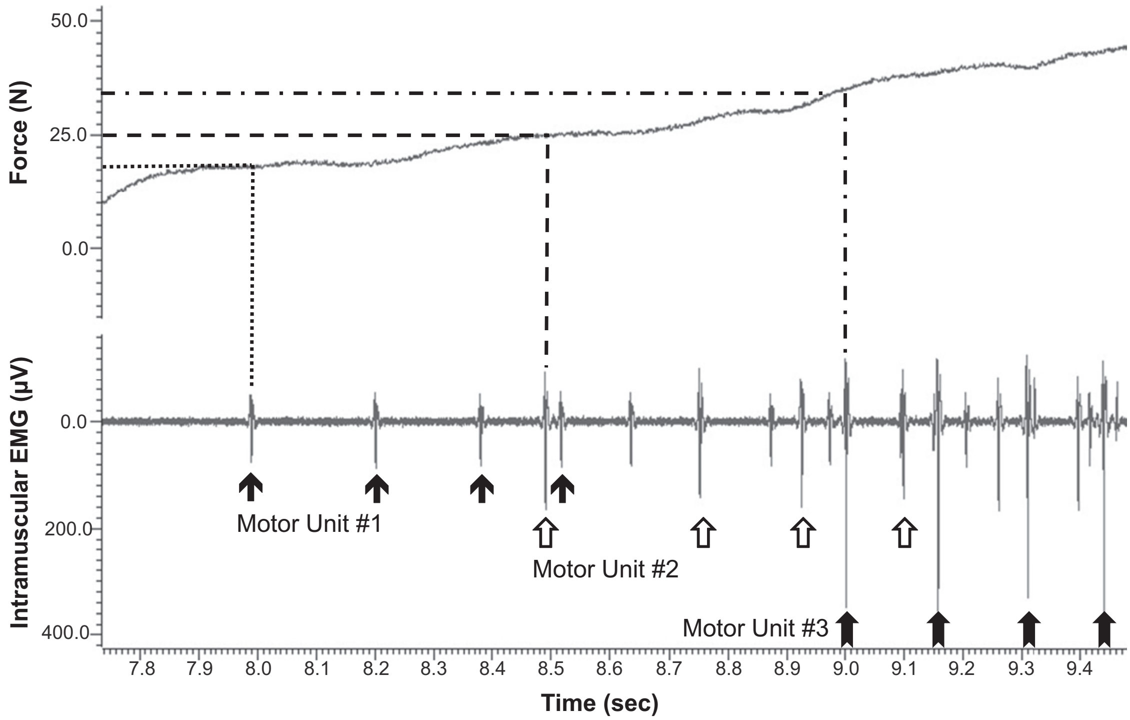

Fig. 1. Single motor unit data reduction. Recruitment threshold for each single motor unit was identified as the force at which the first of four consecutive spikes occurred. Initial firing rates and recruitment thresholds were calculated and recorded for each single motor unit.

lation. In the linear mixed models, the first level was single motor unit. Single motor units were nested according to each subject to form the second level, which was defined as the subject level. Muscle and hip position were the predictor variables for the motor unit level, while sex was the predictor variable for the subject level. There were three implied cross-level interactions, one 3-way interaction among muscle, hip position, and sex, and two 2-way interactions between muscle and sex, and hip position and sex. The absolute force at which a single motor unit was recruited was used as a covariate for initial firing rate due to the correlation between recruitment threshold and initial firing rate (31). Because the firing patterns of single motor units are correlated within an individual participant, we assessed the intraclass correlation of initial firing rates at the subject level in the mixed model. We checked the assumption of normality of residuals and ensured that the linearity and equal variance within each level were not violated. The linear mixed model equation for initial firing rate were written as follows.

The *level 1* equation was:

$$\text{Initial firing rate}_{ij} = \beta_{0j} + \beta_{1j}\text{Muscle}_{ij} + \beta_{2j}\text{Hip position}_{ij} + \beta_{3j}\text{Muscle} \times \text{Hip position} + \beta_{4j}\text{Force} + e_{tij}$$

The *level 2* equations were:

$$\beta_{0j} = \gamma_{00} + \gamma_{01}\text{Sex} + u_{0j}$$

$$\beta_{1j} = \gamma_{10} + \gamma_{11}\text{Sex}$$

$$\beta_{2j} = \gamma_{20} + \gamma_{21}\text{Sex}$$

$$\beta_{3j} = \gamma_{30} + \gamma_{31}\text{Sex}$$

$$\beta_{4j} = \gamma_{40}$$

The majority of the single motor units, 531 of 654 motor units, were recruited within the lower force level of 25% MVC. The natural logarithm transformation was used on the raw recruitment threshold data to meet the assumptions of normality of residuals and constant variance within each level. Further statistical analysis for recruitment threshold was performed on the transformed data, and the mixed model equations were written as below. To help the interpretation of the findings, the recruitment threshold data presented in the figures were exponentiated back to the original units as the percentage of the MVC. We did not use the averaged absolute force as a covariate because of the clear mathematical relation.

The *level 1* equation was:

$$\text{Recruitment threshold}_{ij} = \beta_{0j} + \beta_{1j}\text{Muscle}_{ij} + \beta_{2j}\text{Hip position}_{ij} + \beta_{3j}\text{Muscle} \times \text{Hip position} + e_{tij}$$

The *level 2* equations were:

$$\beta_{0j} = \gamma_{00} + \gamma_{01}\text{Sex} + u_{0j}$$

$$\beta_{1j} = \gamma_{10} + \gamma_{11}\text{Sex}$$

$$\beta_{2j} = \gamma_{20} + \gamma_{21}\text{Sex}$$

$$\beta_{3j} = \gamma_{30} + \gamma_{31}\text{Sex}$$

The differences in the absolute MVC force were tested by a two-way repeated-measures ANOVA (with 1 between factor of sex and 1 within factor of hip position) and Bonferroni post hoc tests.

RESULTS

Motor unit recordings. A total of 654 motor units were recorded from the 26 participants. The distributions of the number and percentage of single motor units between the levels of each predictor variable are shown in Table 1.

Initial motor unit firing rate at recruitment. The subject-level intraclass correlation was 0.23, showing that initial motor unit firing rates were mildly correlated within individuals. There was a main effect for sex [$F(1,26) = 4.77$, $P = 0.04$] and a main effect for hip position [$F(1,630) = 6.45$, $P = 0.01$] on initial firing rate. Averaged across the two hip positions after controlling for force, Tukey's post hoc analysis revealed that initial motor unit firing rates of the pooled data for the VM

Table 1. *Distributions of the number and percentage of single motor units between levels of each predictor variable*

Predictor Variables	No. of Motor Units (Percentage)
Sex	
Male	359 (54.9%)
Female	295 (45.1%)
Muscle	
Vastus medialis	302 (46.2%)
Vastus medialis oblique	352 (53.8%)
Hip position	
Lateral rotation	324 (49.5%)
Neutral rotation	330 (50.5%)

and VMO were higher in women (9.64 ± 0.40 Hz) than in men (8.46 ± 0.39 Hz) [$t(28) = 2.10$, $P = 0.045$; Fig. 2, *left*].

Initial motor unit firing rates were lower during lateral hip rotation than during no hip rotation [$t(637) = 2.52$, $P = 0.01$], with averaged results over the levels of sex and muscle, after controlling for force. Motor units in the VM and VMO fired at slower rates during lateral hip rotation (8.81 ± 0.30 Hz) than during no hip rotation (9.29 ± 0.30 Hz) (Fig. 2, *right*). A trend for an interaction effect between muscle and hip position was observed for possible effect on initial firing rate [$F(1, 629) = 3.17$, $P = 0.08$] (Fig. 3).

Recruitment thresholds. The linear mixed model revealed a main effect for muscle [$F(1,641) = 4.94$, $P = 0.03$] and a main effect of hip position [$F(1,633) = 8.91$, $P < 0.01$] on the log-transformed recruitment thresholds. Averaged across sex and hip position, Tukey's post hoc analysis revealed that recruitment threshold was lower in the VMO than in the VM [$t(648) = -2.21$, $P = 0.03$; VMO: 11.89 ± 1.18%MVC; VM: 14.81 ± 1.24%MVC] (Fig. 4, *left*). Higher recruitment thresholds were observed during lateral hip rotation than during no hip rotation [$t(639) = -2.97$, $P < 0.01$], with results averaged over the levels of sex and muscle. Motor units in both muscles were activated at lower forces during no hip rotation (11.48 ± 1.21%MVC) than during lateral hip rotation (15.22 ± 1.21% MVC) (Fig. 4, *right*). There was a borderline interaction effect between sex and hip position [$F(1, 633) = 3.70$, $P = 0.0547$] (Fig. 5).

Absolute MVC force. There was a significant interaction effect between sex and hip position on the absolute MVC force ($F = 6.948$; $P = 0.01$). Men exhibited a significantly higher absolute MVC force in SLR with neutral hip rotation than SLR with lateral hip rotation ($P < 0.05$). They also showed a significantly higher mean absolute MVC force than female participants in both neutral ($P < 0.05$; men 147.48 ± 35.42 N; women 96.79 ± 26.23 N) and lateral ($P < 0.05$; men 127.08 ± 23.89 N; women 91.90 ± 27.44 N) hip rotation positions (Fig. 6). However, women did not demonstrate different absolute MVC forces between hip positions ($P > 0.05$).

DISCUSSION

The primary goal of the study was to examine if control of the VMO and VM are neurologically distinct during the performance of different exercises. We examined how lateral hip rotation during a SLR affects selective activation of the VMO and VM between sexes. The results of this study confirm clinical theory that healthy individuals recruit motor units within the VMO at an earlier force level compared with motor units within the VM, indicating that the VMO serves as an initial stabilizer of the patella. Female subjects fire motor units in the vastus medialis complex at a faster rate than male subjects after controlling the force. Neutral hip rotation allows motor units to be recruited earlier and to fire at higher rates than lateral hip rotation.

To our knowledge, this is the first study to evaluate differential performance of the VM and VMO in clinical exercise protocols. Numerous studies have endeavored to find the best exercise protocols to properly activate the VMO and generate medially vectored forces on the patella in relation to the VL (10, 13, 15, 24, 26, 41, 45). Although these studies appear to be based on the assumption of the different functions of the VM and VMO, none provided evidence regarding whether partic-

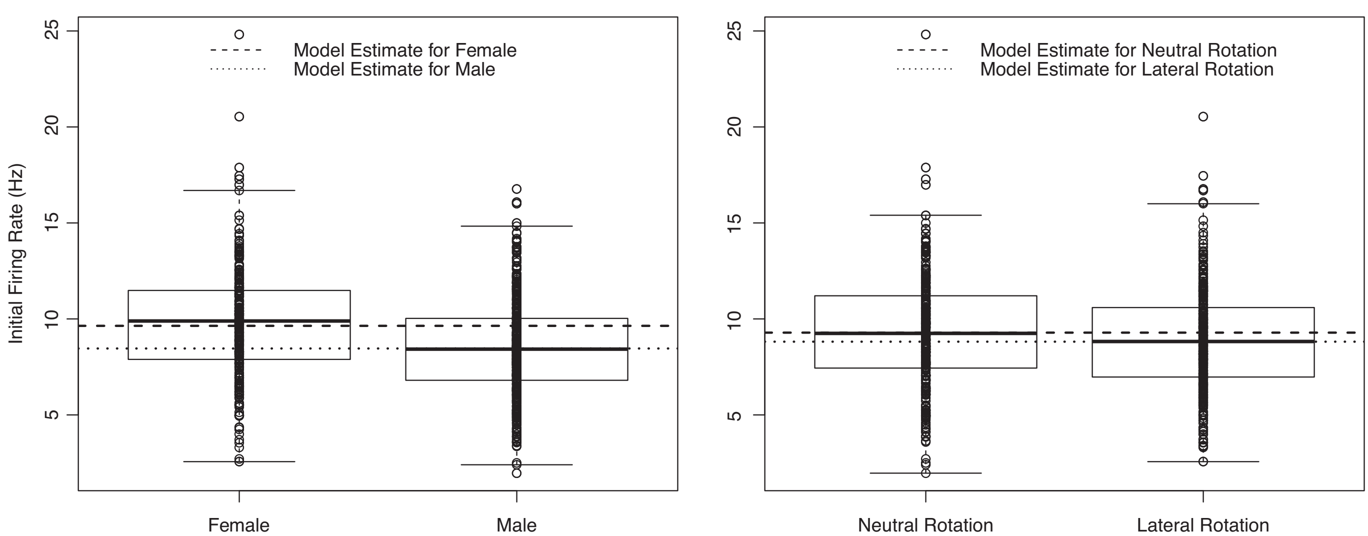

Fig. 2. Data distributions of initial firing rates at recruitment and model estimates from linear mixed models in women and men with pooled averages over levels of muscle and hip position (*left*) and in neutral and lateral hip rotation with pooled averages over levels of sex and muscle (*right*). The circles indicate the raw data points. The broken lines represent the model estimates for the respective variables. Each box contains the middle 50 percent of values with top and bottom borders representing the 75th and 25th percentile. The solid lines in the box represent the raw data median.

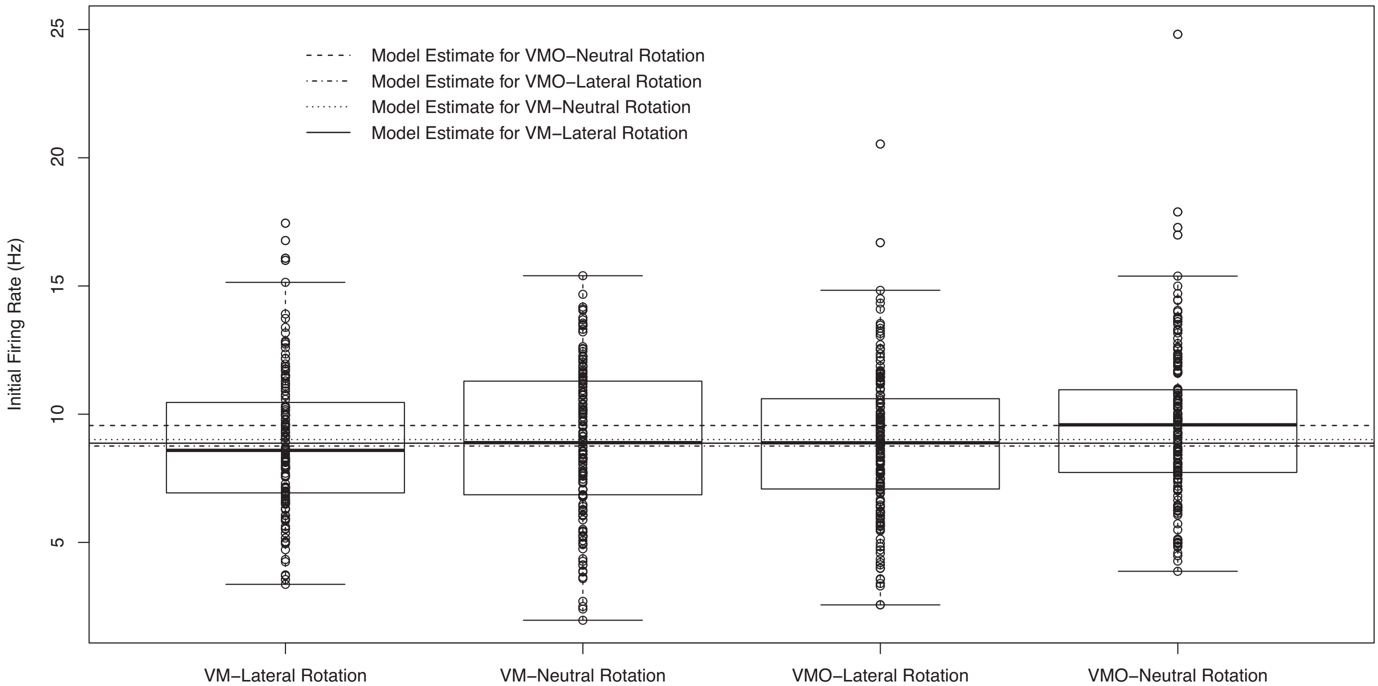

Fig. 3. Data distributions of initial firing rates at recruitment and model estimates from linear mixed models of the VMO and VM in neutral and lateral hip rotation with pooled averages over men and women. The circles indicate the raw data points. The broken/solid lines across the four boxes represent the model estimates for the respective variables. Each box contains the middle 50 percent of values with top and bottom borders representing the 75th and 25th percentile. The thick solid lines in the box represent the raw data median.

ular exercise parameters differentially activated the VMO from the rest of the vastus medialis complex. An effective VMO strengthening protocol is essential for resolving clinical complications and will save time and money spent on therapy visits.

The VM and VMO have some level of sequential activation; the VMO motor units are recruited earlier than the VM motor units at lower force level suggesting that these two muscles are functionally distinct. The muscle fibers of the VM align vertically, generally running within 10–35° to the longitudinal axis

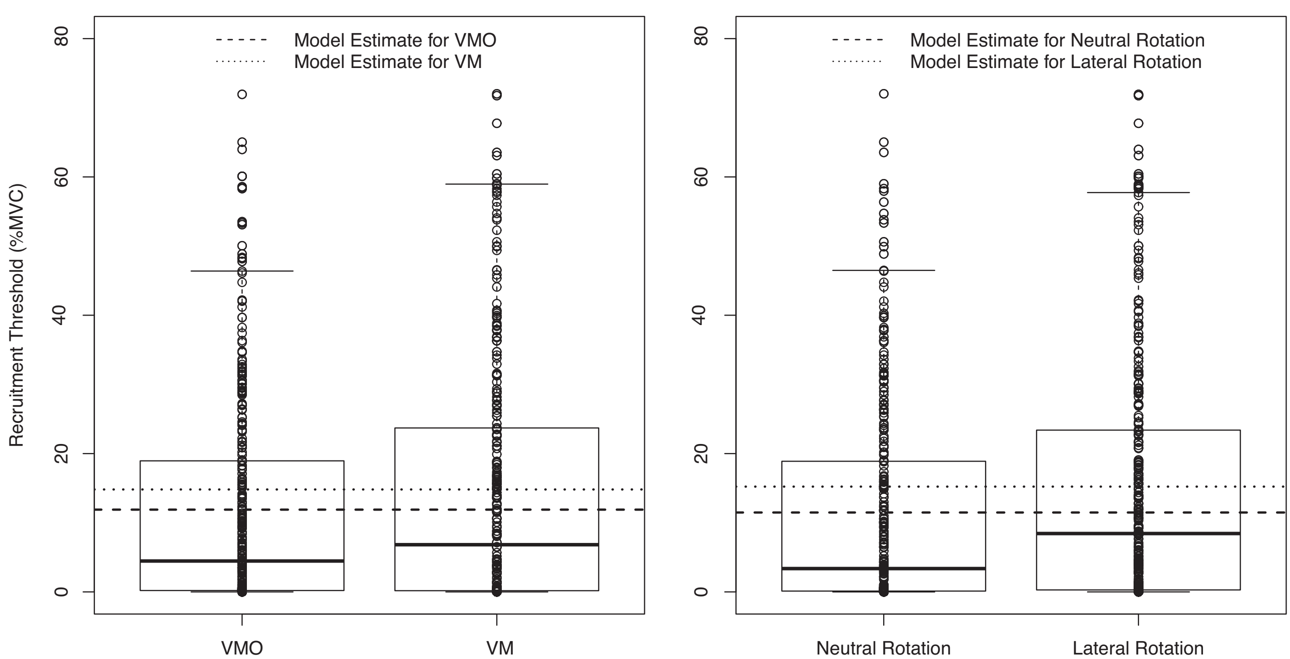

Fig. 4. Data distributions of motor unit recruitment threshold forces and model estimates in the VMO and VM from linear mixed models with pooled averages over levels of sex and hip position (*left*) and in the two hip positions with pooled averages across sex and muscle (*right*). The circles indicate the raw data points. The broken lines represent the model estimates for the respective variables. Each box contains the middle 50 percent of values with top and bottom borders representing the 75th and 25th percentile. The solid lines in the box represent the raw data median.

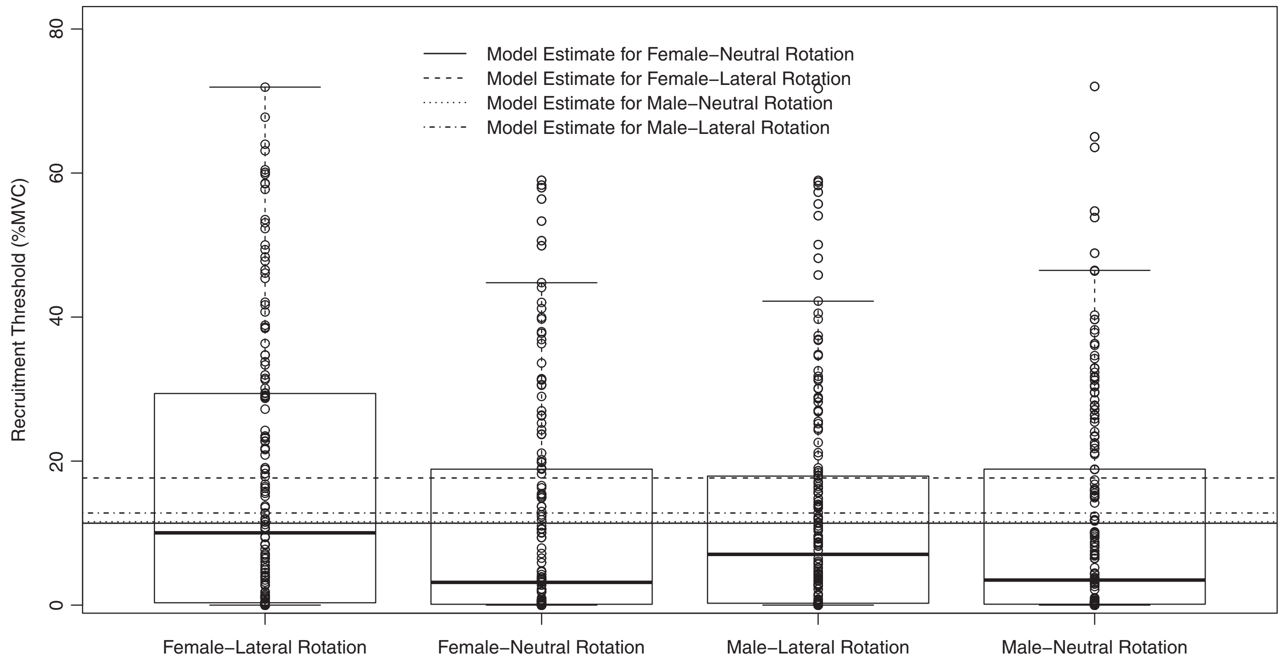

Fig. 5. Data distributions of recruitment thresholds and model estimates from linear mixed models in women and men in neutral and lateral hip rotation with pooled averages over two muscles. The circles indicate the raw data points. The dashed/solid lines across the four boxes represent the model estimates for the respective variables. Each box contains the middle 50 percent of values with top and bottom borders representing the 75th and 25th percentile. The thick solid lines in the box represent the raw data median.

of the femoral shaft, while the fibers of the VMO align more obliquely from 40° to nearly horizontally at the most distal portion (51). The force vectors caused by shortening of the muscle fibers with such divergent orientation contribute to dissimilar patella movements. Evoked VMO contractions pull the patella medially, and the stimulation of the VM guides the patella in a more proximal direction (27). The changing fiber orientation in the vastus medialis complex affects its peak muscle activation area measured by a surface EMG grid in different knee flexion angles (18). The peak amplitude of surface EMG exhibited was higher in the VM than in the VMO during isometric knee extension (18). The summation of current scientific evidence indicates that different subsections of the vastus medialis complex are both mechanically, functionally, and neurologically distinct.

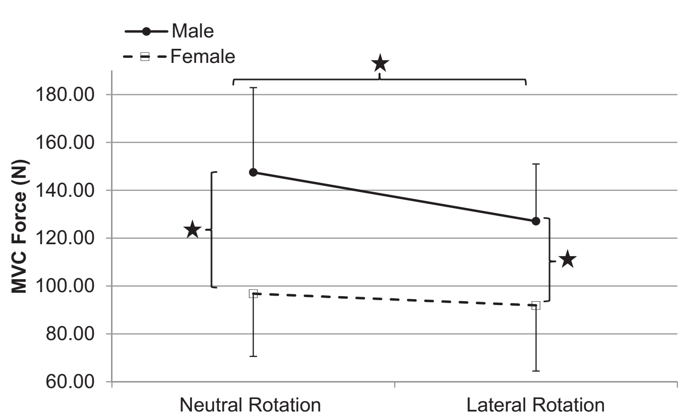

Fig. 6. Means and SDs of MVC force between sex and hip position. ★$P < 0.05$.

Spinal reflex activity of the vastus medialis complex also differs depending on the location of the stimulus applied (17). Regional stretch reflexes are more distal in response to a distal stimulus, suggesting that drive from the spinal cord also differentially recruits motor neurons in the VM and VMO (17). Cabral et al. (9) have previously shown that motor unit discharge patterns derived from the VM and the VMO are similar within their respective region, but functionally less correlated when the two regions are pooled. In the present study, VMO motor units were recruited earlier than VM motor units at low force levels. The differential recruitment pattern between the VM and VMO may be related to biological differences in the distribution of input resistance of the motor units, or it may be due to a modulation in the nervous system to control movement (18, 48). These results also provide evidence of their distinct chronological functions: the VMO pulls the patella medially in advance of the VM to counteract the lateral force of the VL for patellar alignment.

A trend toward earlier VMO motor unit recruitment was also observed in a seated knee extension task (50). This may not have reached statistical significance because the magnitude and direction of patella translation produced by the contraction of the VMO and VM differs with knee flexion angle (27). In the full knee extension position, the patella shifts medially when the VMO is activated, and the patella glides mainly to the proximal direction when the VM is triggered. With increasing knee flexion angle, there is a decrease in the amount of patella medial translation generated by the VMO compared with the full knee extension position, whereas during knee flexion there is a large medial shift of the patella produced by the VM compared with the fully extended leg position (27). Thus the SLR may be a preferable position to differentiate the early recruitment of the VMO compared with the 90° knee flexion.

In the present study, motor unit recruitment thresholds were lower in the neutral hip positon. The finding that motor units are recruited earlier in the neutral position also supports previous work examining the interference patterns of fine-wire EMG in the VMO during hip rotation (10). Cerny (10) reported greater VMO activation with a neutral hip position than during lateral hip rotation in terminal knee extension and isometric holding. They also monitored the distal part of adductor magnus activity concurrently with the VMO and reported that it was neither contributing to hip lateral rotation nor facilitating the VMO activation (10). Others have suggested that lateral hip rotation facilitates VMO activity (19, 22) because the origin of the VMO attaches to the adductor magnus (5). However, recent anatomic studies have found that the longitudinal aspect of the medial adductor magnus, the ischiocondylar portion adjacent to the VMO and inserting on the adductor tubercle of the medial epicondyle of the femur (7), is innervated by the tibial division of the sciatic nerve (L4, 5, S1, 2, 3) (1). This is different from the innervation of the VMO, which is innervated by the medial branch from the posterior division of the femoral nerve (L1, 2, 3) (51). The ischiocondylar portion of the adductor magnus mainly serves to extend the hip (7), and may not contribute to lateral rotation of the hip.

While moving the knee joint in the sagittal plane, the nervous system may respond to the displacement force applied on the patella by adjusting motor unit activity in the surrounding musculature. When performing a SLR, lateral hip rotation can reduce the knee extension torque required to maintain full knee extension. This requires less VMO activation than a neutral hip position (24). However, more activities of daily life occur with the hip in a neutral position in sagittal plane movements, such as walking, running, and biking. Performing the SLR with neutral hip rotation may generate a more effectively controlled VMO muscle contraction that relates to everyday activity.

Our data show that VM and VMO motor units in female participants exhibit significantly higher initial firing rates at recruitment than in male participants, despite standardizing data collection to the late follicular phase, when women are most similar to men (50). This suggests that sex is indeed a contributing factor for the differences in rate-coding of the vastus medialis complex. The statistically significant 1.18 Hz difference in motor unit firing rates observed between the sexes can contribute substantially to changes in muscle force (34) and is considered to be physiologically meaningful (50, 53). Female subjects exhibit greater proportion of slow twitch fibers and less fast twitch fibers in the VL than male subjects (30, 42). It is possible that differences in motor unit discharge patterns in the VM and VMO reflect differences in motor unit type distributions between the sexes.

The borderline interaction between sex and hip position for recruitment threshold suggests that the female motor units predominantly drove the difference in recruitment thresholds between the two hip positions. Females activate motor units in vastus medialis complex earlier in neutral hip position than in lateral hip rotation, whereas male subjects recruit their motor units at a relatively similar force level for both positions. Thus dissimilar control of the vastus medialis complex in two hip positions during targeted quadriceps strengthening exercise may potentially be more beneficial for female subjects. These sex differences may also be related to the finding that women managed to reach similar absolute force levels of MVC force for both hip positions, yet men had a much lower MVC force in the lateral hip rotation compared with neutral hip rotation.

The VMO accounted for the majority of the difference in initial firing rate at recruitment between the two hip positions. A faster initial firing rate occurred in neutral rotation compared with lateral rotation. Thus SLR with neutral hip rotation is more beneficial for targeting the initial activation of the VMO. Other studies reported that populations of single motor units within a muscle, including the first dorsal interosseous, deltoid, and biceps, can be recruited preferentially for particular movements according to the force direction (12, 20). The preferential recruitment of the VMO when performing a SLR with no hip rotation indicates that regional motor neuron inputs may modulate differential activation of the subregions of the vastus medialis complex.

Future studies are necessary to evaluate other clinical exercise protocols that have been advocated to preferentially activate the VMO for individuals with knee pathology. This will promote more tailored and effective VMO strengthening strategies for both sexes. In summary, we have demonstrated that the VMO motor units are recruited earlier at lower force levels compared with the VM motor units. Women fire their VM and VMO motor units at faster rates at recruitment than men. The SLR with neutral hip rotation is a more effective hip position for strengthening the VMO in healthy individuals.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

Y.-L.P., M.S.T., and L.G. conceived and designed research; Y.-L.P. performed experiments; Y.-L.P. and M.S.T. analyzed data; Y.-L.P., M.S.T., and L.G. interpreted results of experiments; Y.-L.P. prepared figures; Y.-L.P. drafted manuscript; Y.-L.P., M.S.T., and L.G. edited and revised manuscript; L.G. approved final version of manuscript.

REFERENCES

1. **Barrett T, Arthurs OJ.** Adductor magnus: a post-operative illustration of its dual nerve supply. *Clin Anat* 23: 115–119, 2010. doi:10.1002/ca.20886.
2. **Bates D, Maechler M, Bolker B, Walker S.** Fitting linear mixed-effects models using lme4. *J Stat Softw* 67: 1–48, 2015. doi:10.18637/jss.v067.i01.
3. **Bennett WF, Doherty N, Hallisey MJ, Fulkerson JP.** Insertion orientation of terminal vastus lateralis obliquus and vastus medialis obliquus muscle fibers in human knees. *Clin Anat* 6: 129–134, 1993. doi:10.1002/ca.980060302.
4. **Boling M, Padua D, Marshall S, Guskiewicz K, Pyne S, Beutler A.** Gender differences in the incidence and prevalence of patellofemoral pain syndrome. *Scand J Med Sci Sports* 20: 725–730, 2010. doi:10.1111/j.1600-0838.2009.00996.x.
5. **Bose K, Kanagasuntheram R, Osman MBH.** Vastus medialis oblique: an anatomic and physiologic study. *Orthopedics* 3: 880–883, 1980. doi:10.3928/0147-7447-19800901-12.
6. **Bowyer D, Armstrong M, Dixon J, Smith OT.** The vastus medialis oblique:vastus lateralis electromyographic intensity ratio does not differ by gender in young participants without knee pathology. *Physiotherapy* 94: 168–173, 2008. doi:10.1016/j.physio.2007.08.007.
7. **Broski SM, Murthy NS, Krych AJ, Obey MR, Collins MS.** The adductor magnus "mini-hamstring": MRI appearance and potential pitfalls. *Skeletal Radiol* 45: 213–219, 2016. doi:10.1007/s00256-015-2291-5.
8. **Byrne CA, Lyons GM, Donnelly AE, O'Keeffe DT, Hermens H, Nene A.** Rectus femoris surface myoelectric signal cross-talk during static

contractions. *J Electromyogr Kinesiol* 15: 564–575, 2005. doi:10.1016/j.jelekin.2005.03.002.
9. **Cabral HV, de Souza LML, Mello RGT, Gallina A, de Oliveira LF, Vieira TM.** Is the firing rate of motor units in different vastus medialis regions modulated similarly during isometric contractions? *Muscle Nerve* 57: 279–286, 2018. doi:10.1002/mus.25688.
10. **Cerny K.** Vastus medialis oblique/vastus lateralis muscle activity ratios for selected exercises in persons with and without patellofemoral pain syndrome. *Phys Ther* 75: 672–683, 1995. doi:10.1093/ptj/75.8.672.
11. **Crossley K, Bennell K, Green S, Cowan S, McConnell J.** Physical therapy for patellofemoral pain: a randomized, double-blinded, placebo-controlled trial. *Am J Sports Med* 30: 857–865, 2002. doi:10.1177/03635465020300061701.
12. **Desnedt HE, Gidaux E.** Spinal motoneuron recruitment in man: rank deordering with direction but not with speed of voluntary movement. *Science* 214: 933–936, 1981. doi:10.1126/science.7302570.
13. **Earl JE, Schmitz RJ, Arnold BL.** Activation of the VMO and VL during dynamic mini-squat exercises with and without isometric hip adduction. *J Electromyogr Kinesiol* 11: 381–386, 2001. doi:10.1016/S1050-6411(01)00024-4.
14. **Farahmand F, Sejiavongse W, Amis AA.** Quantitative study of the quadriceps muscles and trochlear groove geometry related to instability of the patellofemoral joint. *J Orthop Res* 16: 136–143, 1998. doi:10.1002/jor.1100160123.
15. **Felicio LR, Baffa AP, Liporacci RF, Saad MC, De Oliveira AS, Bevilaqua-Grossi D.** Analysis of patellar stabilizers muscles and patellar kinematics in anterior knee pain subjects. *J Electromyogr Kinesiol* 21: 148–153, 2011. doi:10.1016/j.jelekin.2010.09.001.
16. **Foss KD, Myer GD, Magnussen RA, Hewett TE.** Diagnostic differences for anterior knee pain between sexes in adolescent basketball players. *J Athl Enhanc* 3: 1814, 2014. doi:10.4172/2324-9080.1000139.
17. **Gallina A, Blouin JS, Ivanova TD, Garland SJ.** Regionalization of the stretch reflex in the human vastus medialis. *J Physiol* 595: 4991–5001, 2017. doi:10.1113/JP274458.
18. **Gallina A, Ivanova TD, Garland SJ.** Regional activation within the vastus medialis in stimulated and voluntary contractions. *J Appl Physiol (1985)* 121: 466–474, 2016. doi:10.1152/japplphysiol.00050.2016.
19. **Hanten WP, Schulthies SS.** Exercise effect on electromyographic activity of the vastus medialis oblique and vastus lateralis muscles. *Phys Ther* 70: 561–565, 1990. doi:10.1093/ptj/70.9.561.
20. **Herrmann U, Flanders M.** Directional tuning of single motor units. *J Neurosci* 18: 8402–8416, 1998. doi:10.1523/JNEUROSCI.18-20-08402.1998.
21. **Herrington L, Blacker M, Enjuanes N, Smith P, Worthington D.** The effect of limb position, exercise mode and contraction type on overall activity of VMO and VL. *Phys Ther Sport* 7: 87–92, 2006. doi:10.1016/j.ptsp.2006.01.003.
22. **Irish SE, Millward AJ, Wride J, Haas BM, Shum GLK.** The effect of closed-kinetic chain exercises and open-kinetic chain exercise on the muscle activity of vastus medialis oblique and vastus lateralis. *J Strength Cond Res* 24: 1256–1262, 2010. doi:10.1519/JSC.0b013e3181cf749f.
23. **Jojima H, Whiteside LA, Ogata K.** Anatomic consideration of nerve supply to the vastus medialis in knee surgery. *Clin Orthop Relat Res* 423: 157–160, 2004. doi:10.1097/01.blo.0000128642.61260.b3.
24. **Karst GM, Jewett PD.** Electromyographic analysis of exercises proposed for differential activation of medial and lateral quadriceps femoris muscle components. *Phys Ther* 73: 286–295, 1993. doi:10.1093/ptj/73.5.286.
25. Kuznetsova A, Brockhoff PB, Christensen RHB. *lmerTest: Tests in Linear Mixed Effects Models. R package version 2.0–32*, 2016. Available at: https://cran.r-project.org.
26. **Laprade J, Culham E, Brouwer B.** Comparison of five isometric exercises in the recruitment of the vastus medialis oblique in persons with and without patellofemoral pain syndrome. *J Orthop Sports Phys Ther* 27: 197–204, 1998. doi:10.2519/jospt.1998.27.3.197.
27. **Lin F, Wang G, Koh JL, Hendrix RW, Zhang LQ.** In vivo and noninvasive three-dimensional patellar tracking induced by individual heads of quadriceps. *Med Sci Sports Exerc* 36: 93–101, 2004. doi:10.1249/01.MSS.0000106260.45656.CC.
28. **Mesfar W, Shirazi-Adl A.** Biomechanics of the knee joint in flexion under various quadriceps forces. *Knee* 12: 424–434, 2005. doi:10.1016/j.knee.2005.03.004.
29. **McConnell J.** The management of chondromalacia patellae: a long term solution. *Aust J Physiother* 32: 215–223, 1986. doi:10.1016/S0004-9514(14)60654-1.
30. **Miller AEJ, MacDougall JD, Tarnopolsky MA, Sale DG.** Gender differences in strength and muscle fiber characteristics. *Eur J Appl Physiol Occup Physiol* 66: 254–262, 1993. doi:10.1007/BF00235103.
31. **Milner-Brown HS, Stein RB, Yemm R.** Changes in firing rate of human motor units during linearly changing voluntary contractions. *J Physiol* 230: 371–390, 1973. doi:10.1113/jphysiol.1973.sp010193.
32. **Myer GD, Ford KR, Hewett TE.** The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *J Electromyogr Kinesiol* 15: 181–189, 2005. doi:10.1016/j.jelekin.2004.08.006.
33. **Neptune RR, Wright IC, van den Bogert AJ.** The influence of orthotic devices and vastus medialis strength and timing on patellofemoral loads during running. *Clin Biomech (Bristol, Avon)* 15: 611–618, 2000. doi:10.1016/S0268-0033(00)00028-0.
34. **Oya T, Riek S, Cresswell AG.** Recruitment and rate coding organisation for soleus motor units across entire range of voluntary isometric plantar flexions. *J Physiol* 587: 4737–4748, 2009. doi:10.1113/jphysiol.2009.175695.
35. **Pal S, Besier TF, Draper CE, Fredericson M, Gold GE, Beaupre GS, Delp SL.** Patellar tilt correlates with vastus lateralis: vastus medialis activation ratio in maltracking patellofemoral pain patients. *J Orthop Res* 30: 927–933, 2012. doi:10.1002/jor.22008.
36. **Peng HT, Kernozek TW, Song CY.** Muscle activation of vastus medialis obliquus and vastus lateralis during a dynamic leg press exercise with and without isometric hip adduction. *Phys Ther Sport* 14: 44–49, 2013. doi:10.1016/j.ptsp.2012.02.006.
37. **Pinheiro J, Bates D, DebRoy S, Sarkar D; R Core Team.** *Linear and Nonlinear Mixed Effects Models. R package version 3.1–125*, 2016. Available at: https://cran.r-project.org.
38. **R Studio Team.** *RStudio: Integrated Development for R*. Boston, MA: RStudio, 2013.
39. **Rainoldi A, Falla D, Mellor R, Bennell K, Hodges P.** Myoelectric manifestations of fatigue in vastus lateralis, medialis obliquus and medialis longus muscles. *J Electromyogr Kinesiol* 18: 1032–1037, 2008. doi:10.1016/j.jelekin.2007.05.008.
40. **Rainoldi A, Melchiorri G, Caruso I.** A method for positioning electrodes during surface EMG recordings in lower limb muscles. *J Neurosci Methods* 134: 37–43, 2004. doi:10.1016/j.jneumeth.2003.10.014.
41. **Serrao FV, Cabral CMN, Berzin F, Candolo C, Monteiro-Pedro V.** Effect of tibia rotation on the electromyographical activity of the vastus medialis oblique and vastus lateralis longus muscles during isometric leg press. *Phys Ther Sport* 6: 15–23, 2005. doi:10.1016/j.ptsp.2004.03.001.
42. **Simoneau JA, Bouchard C.** Human variation in skeletal muscle fiber-type proportion and enzyme activities. *Am J Physiol Endocrinol Metab* 257: E567–E572, 1989. doi:10.1152/ajpendo.1989.257.4.E567.
43. **Singerman R, Berilla J, Davy DT.** Direct in vitro determination of the patellofemoral contact force for normal knees. *J Biomech Eng* 117: 8–14, 1995. doi:10.1115/1.2792275.
44. **Stensdotter AK, Hodges P, Ohberg F, Häger-Ross C.** Quadriceps EMG in open and closed kinetic chain tasks in women with patellofemoral pain. *J Mot Behav* 39: 194–202, 2007. doi:10.3200/JMBR.39.3.194-202.
45. **Sykes K, Wong YM.** Electrical activity of vastus medialis oblique muscle in straight leg raise exercise with different angles of hip rotation. *Physiotherapy* 89: 423–430, 2003. doi:10.1016/S0031-9406(05)60076-4.
46. **Syme G, Rowe P, Martin D, Daly G.** Disability in patients with chronic patellofemoral pain syndrome: a randomised controlled trial of VMO selective training versus general quadriceps strengthening. *Man Ther* 14: 252–263, 2009. doi:10.1016/j.math.2008.02.007.
47. **Tenan MS.** Quantifying emergency department visits from sport and recreation: focus on the lower extremity and knee, 1997–2009. *J Athl Train* 51: 309–316, 2016. doi:10.4085/1062-6050-51.4.12.
48. **Tenan MS, Hackney AC, Griffin L.** Entrainment of vastus medialis complex activity differs between genders. *Muscle Nerve* 53: 633–640, 2016. doi:10.1002/mus.24897.
49. **Tenan MS, Marti CN, Griffin L.** Motor unit discharge rate is correlated within individuals: a case for multilevel model statistical analysis. *J Electromyogr Kinesiol* 24: 917–922, 2014. doi:10.1016/j.jelekin.2014.08.014.
50. **Tenan MS, Peng YL, Hackney AC, Griffin L.** Menstrual cycle mediates vastus medialis and vastus medialis oblique muscle activity. *Med Sci Sports Exerc* 45: 2151–2157, 2013. doi:10.1249/MSS.0b013e318299a69d.

51. **Thiranagama R.** Nerve supply of the human vastus medialis muscle. *J Anat* 170: 193–198, 1990.
52. **Travnik L, Pernus F, Erzen I.** Histochemical and morphometric characteristics of the normal human vastus medialis longus and vastus medialis obliquus muscles. *J Anat* 187: 403–411, 1995.
53. **Tucker K, Butler J, Graven-Nielsen T, Riek S, Hodges P.** Motor unit recruitment strategies are altered during deep-tissue pain. *J Neurosci* 29: 10820–10826, 2009. doi:10.1523/JNEUROSCI.5211-08.2009.
54. **Van Cutsem M, Duchateau J, Hainaut K.** Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *J Physiol* 513: 295–305, 1998. doi:10.1111/j.1469-7793.1998.295by.x.
55. **Wong YM, Straub RK, Powers CM.** The VMO:VL activation ratio while squatting with hip adduction is influenced by the choice of recording electrode. *J Electromyogr Kinesiol* 23: 443–447, 2013. doi:10.1016/j.jelekin.2012.10.003.