Atrophy of the Quadriceps is Not Isolated to Vastus Medialis Oblique in Individuals with Patellofemoral Pain

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ABSTRACT

Study design: Cross-sectional.

Objectives: To determine if quadriceps atrophy was present in people with patellofemoral pain (PFP), and whether vastus medialis oblique (VMO) was selectively involved.

Background: It has been suggested that selective atrophy of VMO relative to vastus lateralis could be associated with PFP, despite a lack of studies investigating individual quadriceps muscle size in individuals with PFP.

Methods: The quadriceps muscle size of 35 participants with PFP (22 with unilateral and 13 with bilateral symptoms) and 35 asymptomatic control participants matched for age and gender were measured using real-time ultrasound. The thickness of the VMO, vastus lateralis, vastus medialis, rectus femoris, and vastus intermedius were measured. Paired samples t-tests were used to compare muscle thickness between limbs in those with unilateral PFP, and independent t-tests were used to compare muscle thickness between groups with and without PFP.

Results: In those with unilateral PFP, the thickness of all portions of the quadriceps muscle was statistically smaller in the symptomatic compared to the asymptomatic limb: VMO (P=.038), vastus medialis (P<.001), vastus lateralis (P=.005), vastus intermedius (P=.013), rectus femoris (P=.045). No difference was found for the thickness of any portions of the quadriceps in people with PFP compared to asymptomatic controls: VMO (P=.148), vastus medialis (P=.474), vastus lateralis (P=.122), vastus intermedius (P=.466), rectus femoris (P=.508).

Conclusion: Atrophy of all portions of the quadriceps muscles is present in the affected limb of people with unilateral PFP. There was no atrophy of the quadriceps in individuals with
PFP compared to those without pathology. Selective atrophy of VMO relative to vastus lateralis was not identified in people with PFP.

**Key Words:** anterior knee pain, chondromalacia, quadriceps femoris, ultrasound imaging, VMO
INTRODUCTION

Patellofemoral pain (PFP) is a common source of knee pain in active adolescents\(^2^8\) and adults,\(^1^5\) particularly those involved in running and jumping activities.\(^6,8,2^4\) Exercises that aim to selectively improve the strength or contraction timing of vastus medialis oblique (VMO) relative to vastus lateralis (VL) are common used in PFP rehabilitation.\(^1^3,3^1\) These exercises are typically provided under the assumption that there is dysfunction of the VMO, presenting as selective weakness, atrophy, or inhibition.\(^2\) It is not clear if these exercises are appropriate in PFP rehabilitation, as there is no consensus on whether VMO dysfunction is present in individuals with PFP, and how to assess this potential dysfunction.

Parameters suggestive of muscle force production may be assessed with measures of muscle strength, activation (electromyography), or size. It is impossible to investigate whether selective dysfunction of VMO relative to VL exists in people with PFP using strength measurements as the force contribution of the individual quadriceps heads cannot be measured in vivo. Electromyography has been used in research and clinical practice to assess for delayed activation of VMO in individuals with PFP. However, there are inconsistent results from these studies as to whether VMO activation is delayed,\(^4\) and it is difficult for clinicians to discern what constitutes a clinically relevant delay in VMO contraction.\(^1^7\)

Quadriceps muscle thickness (a parameter of muscle size) has been strongly correlated to quadriceps maximum voluntary contraction,\(^3^0\) which suggests that muscle thickness is indicative of muscle force. The measurement and comparison of muscle size between individual portions of the quadriceps muscles may be a valid alternative to distinguishing between selective VMO dysfunction and whole quadriceps dysfunction.

Muscle size is a surrogate of muscle power,\(^2^6\) and muscle atrophy (reduced muscle size) is suggestive of muscle weakness.\(^2^5\) Selective atrophy of VMO has been speculated to occur in
individuals with PFP, and is often used as a justification for targeted VMO exercises. However there is a paucity of literature comparing the size of VMO relative to VL between PFP and asymptomatic limbs. Only 1 study has measured VMO and VL size in individuals with PFP in comparison to a control group, and there are no published data comparing differences between limbs in individuals with unilateral PFP. Further investigation into the relative size of VMO and VL in individuals with PFP is required to determine if it is appropriate to use selective VMO atrophy to justify targeted VMO strengthening.

Real-time ultrasound can be used to measure parameters of muscle size, and is a suitable tool to investigate muscle atrophy through measures of muscle thickness. The availability of real-time ultrasound in many physiotherapy clinics could allow clinicians to differentiate between selective VMO and whole quadriceps atrophy in individuals with PFP.

The aims of this study were to measure the individual portions of the quadriceps muscles (vastus medialis [VM], VMO, VL, rectus femoris [RF], and vastus intermedius [VI]) with real time ultrasound to determine which portions of the quadriceps were potentially atrophied in individuals with PFP, and to investigate if there was selective atrophy of VMO relative to VL. A secondary aim of the study was to determine how prevalent quadriceps atrophy was in individuals with PFP.

METHODS

Participants

Posters were placed in physiotherapy and medical clinics to recruit individuals with PFP and asymptomatic controls. Participants with PFP were matched to controls by age, gender, and lower limb dominance. Power calculating software (GPower 3.1.3, Franz Faul, Germany) was used a-priori to determine that a sample of 52 participants was required to detect a large
difference (effect size \( \geq 0.8 \)) between limbs. Procedures were approved by the La Trobe University Faculty Human Ethics Committee. Participants in this study provided written informed consent and their rights were protected.

**Inclusion criteria**

Participants were eligible for inclusion if they had symptoms for 6 weeks or more, were between 18 and 40 years of age, and were diagnosed with PFP. PFP diagnosis was based on subjective and objective criteria similar to those used in previous studies,\(^1\)\(^-\)\(^7\) and potential participants were included if they had all of the following: pain in the anterior knee region; atraumatic onset of symptoms; anterior knee pain with 2 or more of the following: running, hopping, squatting, stair negotiation, kneeling, or prolonged sitting; anterior knee pain with at least 2 of the following: palpation of the peripatellar region, compression of the patellofemoral joint, resisted isometric contraction at 0, 30, 60, and 90 degrees of knee flexion; and maximal pain during the past week of at least 3 out of 10 on a numerical pain rating scale.

**Exclusion criteria**

Potential control and PFP participants were excluded if they had any history of surgery or significant injury to either lower extremities that resulted in a period of non-weight bearing, back pain, or any internal knee derangement.

In addition, potential participants with PFP were excluded if other potential sources of anterior knee pain (patellar tendinopathy, Hoffa’s fat pad syndrome, infrapatellar or suprapatellar bursitis, patellar dislocation/subluxation) was identified. Potential participants with pain isolated to the inferior pole of the patella on palpation were also excluded.

**Demographic data**
Data on demographics and factors that could be associated with quadriceps muscle size were obtained for all participants. These data included age, gender, height, weight, body mass index (BMI), thigh girth, limb dominance, and activity level (Marx scale). In the PFP group, symptom duration, symptom severity measured on a 0-10 visual analog scale, and the self-reported Kujala scale for anterior knee pain were also recorded (TABLE 1).

**Procedures**

Ultrasound assessment of both quadriceps was performed on all consenting participants. To determine the location to perform ultrasound measurements of the individual portions of the quadriceps muscle, an anthropometric tape measure was used to measure the distance from the superior tip of the patella to the anterior superior iliac spine (ASIS). The thickness of the VM was measured at 20% of this distance, thickness of the VI, VL, and RF at 50% of this distance, and thickness of the VMO at 2 cm above the patella. These locations were based on data from the work of Kawakami et al and are intended to correspond to the maximum cross sectional area (CSA) of each individual section of the quadriceps muscle. To account for the medial location of the VM and VMO, measurements were taken at 12.5% of thigh circumference in the medial direction, and to account for the lateral location of the VL, measurements were taken at 10% of thigh circumference in the lateral direction. These measurement points were marked with a pen to allow identification during ultrasound measurements (FIGURE 1).

**Ultrasound**

All measurements were performed by a physiotherapist with specific training in the use of real-time ultrasound. With the participant lying supine, a strap was placed around both feet to prevent hip external rotation. Ultrasound measurements (HDI3000 by Advanced Technology Laboratories, California) were made by placing a 38mm, 13-18Hz linear transducer over each
of the previously identified locations. The images were taken with the probe angled so that the femur was visible and centred in the screen. The depth of the image was adjusted until the femur was visible on screen, and the gain was adjusted until muscle boundaries were also visible on screen. Three images were taken of each muscle and saved in a de-identified format for subsequent analysis. The average of the measures from the 3 images was used for analysis. Sufficient ultrasound gel was used to reduce muscle compression with the transducer head. The person capturing the images could not be blind to all participant symptoms; therefore images were stored in a de-identified format to blind the person performing the measurements to group allocation.

**Data Analysis**

Stored DICOM images were retrieved from the ultrasound unit, and Image J software was used to measure muscle thickness. Muscle thickness of VMO, VM, and VI was defined as the distance between the superficial border of the muscle to the most superficial aspect of the femur. Thickness of VL and RF was defined as the distance between the superficial border of the muscle to the deep border in the direction of the most superficial aspect of the femur (FIGURE 2).

**Validity of real-time ultrasound muscle thickness measurements.**

Measurements of muscle thickness were used because it is not feasible to measure CSA with ultrasound in a clinical setting. A previous investigation into the validity of ultrasound muscle thickness measurements to estimate muscle thickness reported the correlation (Pearson’s correlation coefficient (r)) between ultrasound and magnetic resonance imaging (MRI) values of muscle thickness as follows: VMO (0.86), VM (0.86), VL (0.94), VI (0.37), RF (0.86)). The correlation (Spearman’s correlation coefficient (rho)) between ultrasound muscle thickness and MRI CSA measures were as follows: VMO (0.20), VM (0.73), VL (0.83), VI
The intrarater reliability of individual ultrasound measures was assessed using intraclass correlation coefficient (ICC) by comparing the measures taken from 3 separate images for each muscle in 68 participants. The reliability of the measurements was excellent with ICC values ranging from 0.96 to 0.98.

**Statistical analysis**

Statistical Package for Social Sciences (SPSS) was used for all data analyses.

For those with unilateral PFP, paired samples t-tests were used to compare thickness of each portion of the quadriceps muscle, and the proportion in thickness of VM and VMO relative to VL, between the symptomatic limbs and the contralateral asymptomatic limbs. Statistical significance was set at $P \leq 0.05$ for all analyses.

To determine how common quadriceps atrophy is in individuals with PFP, the proportion of participants with unilateral PFP who were classified as having quadriceps atrophy was calculated. To determine what could be considered atrophy, the 95% confidence interval (CI) of the mean for the absolute difference in muscle thickness between limbs for the control group was calculated. The lower bound of the 95% CI was 8.5%. Therefore, quadriceps atrophy was determined based on a deficit of 8.5% or greater in the sum of thickness values in the affected limb compared to the unaffected limb.

To determine whether there was a net trend for quadriceps atrophy, the sum of the thickness measurements from each individual portion of the quadriceps muscle was calculated. This total quadriceps thickness value was compared between symptomatic limbs and the matched limbs of the control group, and between symptomatic and asymptomatic limbs in those with unilateral PFP.
To evaluate differences in muscle thickness between PFP limbs (affected limb of those with unilateral symptoms and the most painful limb of those with bilateral symptoms) and limbs from the control group, independent samples t-tests were performed. For data analysis, limb for the PFP and control groups were matched based on dominance. This analysis was performed for the muscle thickness of VM, VL, VMO, VI, and RF.

To determine if differences were present in the relative size of the medial and lateral quadriceps in individuals with PFP, differences in the proportion in muscle thickness of VM relative to VL, and VMO relative to VL were investigated, and compared to individuals in the control group.

**RESULTS**

A total of 70 participants were recruited. Of the 35 participants with PFP, 22 had unilateral symptoms and 13 had bilateral symptoms. Seven (32%) of the 22 participants with unilateral PFP had symptoms in their dominant (kicking) limb. There was no statistically significant difference between groups in height, weight, or activity level (TABLE 1).

**Individuals with unilateral PFP**

Significantly smaller muscle thickness was identified for the VMO, VM, VL, VI, and RF, as well as the total quadriceps (sum of all individual measures), between symptomatic and asymptomatic limbs in individuals with unilateral PFP (TABLE 2). No significant difference between limbs was found for the thickness ratio of VMO relative to VL, and VM relative to VL.
Smaller total quadriceps muscle thickness (greater than 8.5% deficit) was found in the symptomatic limb of 10 (45%) of the 22 participants with unilateral symptoms, when compared to the asymptomatic limb.

**Between groups comparisons**

The muscle thickness of the VMO, VM, VL, VI, and RF in the limb of those with PFP was not significantly different to the thickness of the same muscles of the matched limb of those in the control group (**TABLE 3**). Similarly, the ratio in muscle thickness of VMO relative to VL and of VM relative to VL was no different between PFP and control limbs.

**DISCUSSION**

This study showed that each portion of the quadriceps muscle was smaller in the affected limb of individuals with unilateral PFP when compared to their unaffected limb, and that in the affected limb, the VMO was not selectively smaller than the VL. No significant difference was found in quadriceps muscle thickness between the symptomatic limbs of those with PFP and the matched limbs from asymptomatic participants. In combination, these results suggest that atrophy of each individual quadriceps head is present in individuals with unilateral PFP, and that there is no difference in the amount of atrophy of VMO relative to VL in those with PFP.

A systematic literature review with meta-analysis, published in 2013, concluded that there was quadriceps atrophy between limbs in individuals with unilateral PFP. However, there was a lack of data on whether the atrophy was present throughout the quadriceps or isolated to a specific section of the quadriceps (eg, the VMO). To our knowledge, this current study is the first to investigate and identify atrophy of each portion of the quadriceps muscle (VMO,
VM, VL, VI, and RF) between limbs of people with unilateral PFP, and the results showed that atrophy of the quadriceps, as defined by a difference between limbs of at least 8.5%, is common, being found in 45% of those with unilateral PFP.

The previously published systematic review also found the presence of quadriceps atrophy in people with PFP when compared to an asymptomatic population. One previous study had measured each individual sections of the quadriceps and found atrophy of the VL at the mid thigh and of the VMO at the distal thigh region between symptomatic and asymptomatic participants. Another study found VMO atrophy in those with PFP but did not measure the other portions of the quadriceps. The finding of this study that there was no significant difference in the thickness of any of the portions of the quadriceps between people with and without PFP was inconsistent with the conclusion of quadriceps atrophy in the systematic review. This could be explained by an unknown difference in baseline characteristic between groups beyond age, height, weight, limb dominance, or gender, which were all similar.

Selective atrophy of VMO relative to VL is often suggested to be present in individuals with PFP despite a lack of supporting data. One previous study has investigated the size of the VMO relative to the VL and found no difference between people with and without PFP. The findings of the current study are consistent with those of Pattyn et al. and suggest there is no selective atrophy of VMO in people with PFP when compared to asymptomatic control participants. Additionally, to our knowledge, this is the first study to investigate the size of VMO relative to VL in individuals with unilateral PFP, and the findings suggest there is also no selective atrophy of VMO of the affected limb in this population when compared to their unaffected limb.
It is impossible from these data to determine if smaller quadriceps size is a predisposing factor to PFP, or if it occurs after the onset of pain. Lesser quadriceps strength has been identified as a risk factor for PFP, and it is reasonable to expect that lesser strength is associated with smaller quadriceps size.

**CLINICAL RELEVANCE**

Selective atrophy of VMO is often inferred from visual inspection of the quadriceps, especially the VMO bulk, in the clinical examination of individuals with PFP. The medial location, and the teardrop shape, of the VMO may make it the easiest portion of the quadriceps for which to compare muscle bulk between limbs. The finding that atrophy is present throughout the quadriceps in individuals with unilateral PFP suggests that caution should be applied when interpreting reduced VMO bulk on visual inspection to be selective atrophy of VMO.

Exercises targeting VMO are typically prescribed on the premise that there is selective dysfunction of VMO relative to VL. The results from the current study, combined with results from previous research, suggest that there is no difference in the size of VMO relative to VL in individuals with PFP. This, combined with a systematic review that did not identify a significant delay in VMO contraction in individuals with PFP, questions the justification of selective VMO dysfunction and attempts to selectively activate VMO in PFP rehabilitation. It is also unclear that any exercises can preferentially activate and strengthen the VMO. If selective VMO dysfunction does exist in individuals with PFP, future research investigating alternative methods of identifying and rehabilitating selective VMO dysfunction are required.

The findings of this study suggest that real-time ultrasound may be a suitable tool to detect quadriceps atrophy in individuals with unilateral PFP. Quadriceps muscle thickness
measurements can be performed relatively quickly with ultrasound, and it is feasible for clinicians to use these measurements in clinical assessment. However, it is difficult for clinicians to assess for quadriceps atrophy in people with bilateral symptoms. The data from unilateral PFP suggest that quadriceps atrophy is common in people with PFP (45% of our participants), and when extrapolating these data to those with bilateral symptoms, the high likelihood that quadriceps atrophy is present should be taken into consideration when deciding if quadriceps strengthening exercises are appropriate.

Limitations

Caution is advised in extrapolating the results from between group analysis to suggest there is no quadriceps atrophy in individuals with PFP as the results are in contrast to findings of a recent meta-analysis that found quadriceps atrophy in those with PFP. The validity of ultrasound thickness measurements of the VI was poor. The VMO measurement was strongly correlated to MRI measurement of muscle thickness and poorly to muscle CSA, caution should be applied in extrapolating the findings of VMO thickness to that of gross VMO morphology. The assessor was blind to group allocation when measuring muscle thickness but not when the images were captured. The muscle thickness measurements were performed at rest, the relationship between VMO and VL morphology during the contracted state could be different.

CONCLUSION

In individuals with unilateral PFP, smaller muscle thickness of the VM, VMO, VL, RF, and VI was found in their affected limb when compared to their contralateral side. In this same group, no difference was found in the proportional thickness of the VMO relative to the VL between limbs, suggesting that atrophy is not specific to the VMO. These findings suggest that atrophy is present in all portions of the quadriceps in individuals with PFP, and that...
exercises with the goal to preferentially activate and strengthen the VMO are not justified in this population.

**KEY POINTS**

**Findings:** The thickness of each portions of the quadriceps muscle is smaller in the affected limb of people with unilateral PFP.

**Implications:** Strengthening interventions should target the entire quadriceps and exercises with the goal to preferentially activate and strengthen the VMO are not justified in this population.

**Caution:** This study does not establish whether the quadriceps atrophy is a cause or effect of PFP.
REFERENCES


### Table 1

<table>
<thead>
<tr>
<th>Group characteristics*</th>
<th>PFP (n=35)</th>
<th>Control (n=35)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>28.2 ± 6.0</td>
<td>28.3 ± 5.8</td>
<td>.968</td>
</tr>
<tr>
<td>Gender (n)</td>
<td>F: 20, M: 15</td>
<td>F: 20, M: 15</td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td>172.5 ± 8.8</td>
<td>171.2 ± 9.6</td>
<td>.552</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>72.6 ± 12.4</td>
<td>72.6 ± 12.7</td>
<td>.992</td>
</tr>
<tr>
<td>Thigh girth (cm)</td>
<td>56.5 ± 3.8</td>
<td>55.6 ± 5.1</td>
<td>.413</td>
</tr>
<tr>
<td>Marx activity score (0-16)**</td>
<td>3.7</td>
<td>2.8</td>
<td>.381</td>
</tr>
<tr>
<td>Kujala scale (0-100)**</td>
<td>77.6 ± 10.5</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Pain severity (0-10)**</td>
<td>5.4</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Abbreviation: PFP, patellofemoral pain

*Data are means ± standard deviations unless otherwise indicated.

**Marx activity score, higher score is more active; Kujala scale, higher score reflects greater function and less symptoms; pain severity, higher score indicates more pain.
**TABLE 2**

Comparison of quadriceps muscle thickness between symptomatic and asymptomatic limbs of 22 participants with unilateral PFP*

<table>
<thead>
<tr>
<th></th>
<th>PFP limb</th>
<th>Asymptomatic limb</th>
<th>Mean difference (95% CI)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMO</td>
<td>2.37 ± 0.37</td>
<td>2.51 ± 0.46</td>
<td>-0.15 (-0.29, -0.01)</td>
<td>.038</td>
</tr>
<tr>
<td>VM</td>
<td>2.95 ± 0.53</td>
<td>3.24 ± 0.52</td>
<td>-0.29 (-0.43, -0.15)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>VL</td>
<td>2.38 ± 0.32</td>
<td>2.52 ± 0.36</td>
<td>-0.14 (-0.23, -0.05)</td>
<td>.005</td>
</tr>
<tr>
<td>VI</td>
<td>1.98 ± 0.51</td>
<td>2.16 ± 0.47</td>
<td>-0.18 (-0.31, -0.04)</td>
<td>.013</td>
</tr>
<tr>
<td>RF</td>
<td>2.27 ± 0.36</td>
<td>2.35 ± 0.34</td>
<td>-0.08 (-0.16, 0.00)</td>
<td>.045</td>
</tr>
<tr>
<td>Quadriceps**</td>
<td>11.95 ± 1.63</td>
<td>12.79 ± 1.75</td>
<td>-0.84 (-1.21, -0.47)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>VMO:VL</td>
<td>1.02 ± 0.17</td>
<td>1.02 ± 0.18</td>
<td>-0.01 (-0.07, 0.06)</td>
<td>.833</td>
</tr>
<tr>
<td>VM:VL</td>
<td>1.25 ± 0.21</td>
<td>1.30 ± 0.22</td>
<td>-0.05 (-0.14, 0.03)</td>
<td>.209</td>
</tr>
</tbody>
</table>

Abbreviations: PFP, patellofemoral pain; RF, rectus femoris; VI, vastus intermedius; VL, vastus lateralis; VM, vastus medialis; VM:VL, ratio of vastus medialis to vastus lateralis; VMO, vastus medialis oblique; VMO:VL, ratio of vastus medialis oblique to vastus lateralis.

*Data are means ± standard deviations in cm except for VMO:VL and VM:VL which are ratios.

**Sum of all 5 sections of the quadriceps.
TABLE 3
Comparison of quadriceps muscle thickness between those with PFP and a matched limb of a control group*

<table>
<thead>
<tr>
<th></th>
<th>PFP group (n=35)</th>
<th>Control group (n=35)</th>
<th>Mean difference (95% CI)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMO</td>
<td>2.37 ± 0.38</td>
<td>2.53 ± 0.49</td>
<td>-0.15 (-0.36, 0.06)</td>
<td>.148</td>
</tr>
<tr>
<td>VM</td>
<td>2.93 ± 0.61</td>
<td>3.04 ± 0.67</td>
<td>-0.11 (-0.42, 0.20)</td>
<td>.474</td>
</tr>
<tr>
<td>VL</td>
<td>2.33 ± 0.33</td>
<td>2.47 ± 0.41</td>
<td>-0.14 (-0.32, 0.04)</td>
<td>.122</td>
</tr>
<tr>
<td>VI</td>
<td>1.88 ± 0.46</td>
<td>1.80 ± 0.48</td>
<td>0.08 (-0.14, 0.31)</td>
<td>.466</td>
</tr>
<tr>
<td>RF</td>
<td>2.30 ± 0.37</td>
<td>2.25 ± 0.30</td>
<td>0.05 (-0.11, 0.21)</td>
<td>.508</td>
</tr>
<tr>
<td>Quadriceps**</td>
<td>11.81 ± 1.73</td>
<td>12.08 ± 2.03</td>
<td>-0.27 (-1.17, 0.63)</td>
<td>.554</td>
</tr>
<tr>
<td>VMO:VL</td>
<td>1.03 ± 0.17</td>
<td>1.03 ± 0.17</td>
<td>0.00 (-0.08, 0.08)</td>
<td>.930</td>
</tr>
<tr>
<td>VM:VL</td>
<td>1.26 ± 0.25</td>
<td>1.24 ± 0.24</td>
<td>0.02 (-0.09, 0.14)</td>
<td>.677</td>
</tr>
</tbody>
</table>

Abbreviations: PFP, patellofemoral pain; RF, rectus femoris; VI, vastus intermedius; VL, vastus lateralis; VM, vastus medialis; VM:VL, ratio of vastus medialis to vastus lateralis; VMO, vastus medialis oblique; VMO:VL, ratio of vastus medialis oblique to vastus lateralis. *Data are means ± standard deviations in cm except for VMO:VL and VM:VL which are ratios.

**Sum of all 5 sections of the quadriceps.
FIGURE 1. Location of ultrasound measurements.

VL, vastus intermedius; VL, vastus lateralis; VM, vastus medialis; VMO, vastus medialis oblique; RF, rectus femoris.
FIGURE 2. Ultrasound measurement of the thickness of vastus lateralis.

Note, vertical white line represents muscle thickness of vastus lateralis.