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# Lower Extremity Muscle Volume in Unilateral and Bilateral Patellofemoral Pain: A Cross-Sectional Exploratory Study Including Superficial and Deep Muscles

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***Context:*** Existing patellofemoral pain (PFP) literature has primarily been focused on quadriceps muscle volume, with limited attention given to the deep and superficial muscle volume of the lower limbs in individuals with unilateral and bilateral PFP. In this paper, we aim to fill this gap.

***Objective:*** To explore superficial and deep lower extremity muscle volume in women with unilateral or bilateral PFP compared with a normative database of pain-free women.

***Design:*** Cross-sectional study.

***Setting:*** University imaging research center.

***Patients or Other Participants:*** Twenty women with PFP (10 unilateral and 10 bilateral) and 8 pain-free women from a normative database.

***Main Outcome Measure(s):*** We quantified lower extremity muscle volume via 3.0-T magnetic resonance imaging. Two separate 1-way analyses of variance were performed: (1) unilateral PFP (painful versus nonpainful limb) versus pain-free control groups and (2) bilateral PFP (more painful versus less painful limb) versus pain-free control groups.

***Results:*** We observed no differences in age and body mass index across groups ($P > .05$). Compared with the pain-free group, the unilateral and bilateral PFP groups had bilaterally smaller volumes of the anterior (iliacus: $P \leq .0004$; $d$ range, 2.12–2.65), medial (adductor brevis, adductor longus, gracilis, and pectineus: $P \leq .02$; $d$ range, 1.25–2.48), posterior (obturator externus, obturator internus, and quadratus femoris: $P < .05$; $d$ range, 1.17–4.82), and lateral (gluteus minimus: $P \leq .03$; $d$ range, 1.16–2.09) hip muscles and knee extensors (rectus femoris: $P \leq .003$; $d$ range, 1.67–2.16) and flexors (long and short head of the biceps femoris: $P \leq .01$, $d$ range, 1.56–1.93).

***Conclusions:*** Women with unilateral and those with bilateral PFP displayed less volume of multiple superficial and deep muscles of the bilateral hips and knees than pain-free women. Interventions should bilaterally target lower limb muscles when treating PFP, and hypertrophy exercises for specific muscles should be explored to increase choices for intervention.

***Key Words:*** anterior knee pain, hip, knee, muscle modeling, morphology, bilateral change

**Key Points**

- No differences in muscle volume between the painful limb in the unilateral patellofemoral pain (PFP) group and the more painful limb in the bilateral PFP group suggested a similar magnitude of volumetric reduction between groups.
- Clinicians should be aware of potential bilateral differences in lower extremity muscle volume and use rehabilitation strategies that integrate evidence-based interventions to optimize muscle volume for women with PFP.

Patellofemoral pain (PFP) is a common form of knee pain, with a higher annual prevalence in women (29.2%) than men (15.5%).[1] The condition is exacerbated by weightbearing activities that load the patellofemoral joint, resulting in disability with daily activities and reduced physical activity.[2,3] Individuals with PFP commonly present with long-term pain, with >90% reporting pain 16 years after initial diagnosis.[4]

Although the exact cause is unclear, the most supported cause of PFP is increased stress on the patellofemoral joint, which could result from muscular imbalances of the lower extremity.[5,6] However, limited research is available on the individual muscle volumes of superficial and deep muscles in the lower limbs of individuals with PFP. Recently, positive associations between muscle volume and isometric strength in knee extension and hip abduction were found in a subgroup of the participants included in this study, highlighting the importance of understanding both hip and knee muscle volumes.[7] As such, clinicians may consider targeting smaller muscles through exercises aimed at promoting hypertrophy. Magnetic resonance imaging (MRI) analysis of muscle volume provides a valid approach to understanding the gross muscular function of individual superficial and deep muscles in this population.[8,9]

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Investigating pain distribution, Boudreau et al found that 68.2% of individuals experienced bilateral PFP.[10] However, an individual with unilateral PFP may also experience neuromuscular changes bilaterally.[11,12] Most daily tasks, such as walking, running, and stair negotiation, require the capacity of both limbs. Therefore, bilateral evaluation and treatment of muscle function is important. Although mechanisms of bilateral deficits have not been fully elucidated, patients with unilateral PFP experience various quadriceps neuromuscular dysfunctions (eg, strength, activation, and rate of torque development) in both lower extremities.[11,12] Observations of these bilateral deficits suggest that a nonpainful or less painful limb in patients with unilateral or bilateral PFP, respectively, may also not be an appropriate normal reference. Given that patients with unilateral PFP can have bilateral neuromuscular deficits, researchers need to compare volumetric profiles between individuals with unilateral or bilateral PFP and pain-free controls.[11,12]

The aims of this study were to (1) investigate differences in superficial and deep lower extremity muscle volumes of both limbs in women with unilateral and those with bilateral PFP compared with a normative database of pain-free women from the established data; (2) assess limb asymmetry in muscle volumes in women with unilateral and those with bilateral PFP; and (3) compare muscle volumes between the painful limb in women with unilateral PFP and the more painful limb in women with bilateral PFP.[9] We hypothesized that (1) both women with unilateral and those with bilateral PFP would exhibit bilaterally smaller volumes in superficial and deep hip and knee muscles than pain-free women; (2) both women with unilateral and those with bilateral PFP would display similar levels of limb asymmetry, with inconsistent patterns and heterogeneous volumetric profiles across individual muscles; and (3) no difference would exist in muscle volumes between the painful limb in women with unilateral PFP and the more painful limb in women with bilateral PFP.

## METHODS

### Design

Reporting of this cross-sectional study was in accordance with Strengthening the Reporting of Observational Studies in Epidemiology guidelines.[13] We also adhered to the REPORTing of quantitative PatelloFemoral Pain (REPORT-PFP) guidelines, addressing the reporting of demographics, baseline symptoms, and outcome measures.[14] The reporting guidelines provide standardized recommendations for reporting items within quantitative PFP research.[14] Independent variables were group (unilateral PFP, bilateral PFP, and pain-free control) and limb (unilateral PFP [painful and nonpainful limb], bilateral PFP [more painful and less painful limb], and pain-free control [right-side limb]).[9] Dependent variables were lower extremity muscle volumes (3 anterior [iliacus, psoas major, and sartorius], 5 medial [adductor brevis, adductor longus, adductor magnus, gracilis, and pectineus], 5 posterior [gluteus maximus, obturator externus, obturator internus, piriformis, and quadratus femoris], and 3 lateral [gluteus medius, gluteus minimus, and tensor fasciae latae] hip muscles; 4 knee extensors [rectus femoris, vastus intermedius, vastus lateralis, and vastus medialis]; and 4 knee flexors [long and short heads of the biceps femoris, semimembranosus, and semitendinosus]) measured using a high-resolution MRI-derived muscle modeling technique.[15] We categorized muscles as superficial (sartorius, adductor longus, gracilis, gluteus maximus, gluteus medius, tensor fasciae latae, rectus femoris, vastus lateralis, vastus medialis, long and short heads of the biceps femoris, semimembranosus, and semitendinosus) and deep (iliacus, psoas major, adductor brevis, adductor magnus, pectineus, obturator externus, obturator internus, piriformis, quadratus femoris, gluteus minimus, and vastus intermedius).

### Participants

Twenty women with PFP (10 unilateral and 10 bilateral; age range, 18–35 years) were recruited from a local university and community between February and August 2022 via flyers and social media posts. A subgroup of these participants was included in a previous study.[7] We used the International Patellofemoral Research Retreat Consensus Statement eligibility criteria.[2] Volunteers were included if (1) they had insidious onset of peripatellar or retropatellar pain for >3 months; (2) their worst pain level was >3 cm on a 10-cm visual analog scale in the week before the study; and (3) their pain level was ≥2 during the following tasks: prolonged sitting, squatting, walking, running, and ascending and descending stairs. The exclusion criteria included the following: (1) history of low back or lower extremity surgery; (2) history of low back or lower extremity injury in the year before the study; (3) history of patellar dislocation or subluxation; (4) internal derangement; (5) ligamentous instability; (6) other sources of anterior knee pain (eg, patellar tendinopathy); or (7) neurological impairments. We also screened participants for MRI contraindications as described previously.[7] All participants provided written informed consent, and the study was approved by the University of Connecticut Institutional Review Board (H21-0075).

### Procedures

Participants were referred to a university imaging research center for a single visit. After completing the eligibility screening, they self-reported their age, height, mass, and symptom duration using Qualtrics (Qualtrics Inc) survey software. Individuals with bilateral PFP self-reported the limb that was more painful. We assessed worst pain level in the week before the study using a visual analog scale (0 = *no pain*; 10 = *worst pain imaginable*) and patient-reported outcomes using the Anterior Knee Pain Scale, Knee injury and Osteoarthritis Outcome Score (KOOS) with the patellofemoral subscale, Pain Self-Efficacy Questionnaire, and Pain Catastrophizing Scale.[14,16]

Bilateral muscle volume was assessed with a 3.0-T MRI scanner (Siemens Magnetom Prisma; Siemens Medical Solutions Inc) using the technique previously described.[7,9]

### Data Analysis

Raw muscle volume (in $cm^3$) of each muscle was normalized to the product of participant height and mass (in $cm^3$/kg·m), which is the best predictor of muscle volume for both women and men of various body mass indices ($R^2 = 0.92$).[9] Muscle volume was converted to $z$ scores and compared between the PFP and pain-free groups (Springbok Analytics Inc) as described in previous studies.[7,9] When the difference was $z \geq 3$ SD, muscle volume in the PFP versus the pain-free group was considered to be *extremely larger*; 3 SD $> z \geq$ 2 SD, *moderately larger*; 2 SD $> z \geq$ 1, *slightly larger*; 1 SD $> z \geq -1$ SD, *normal*; $-1$ SD $\geq z > -2$ SD, *slightly smaller*; $-2$ SD $\geq z > -3$ SD, *moderately smaller*; or $z \leq -3$ SD, *extremely smaller*. Volumetric symmetry was calculated as the



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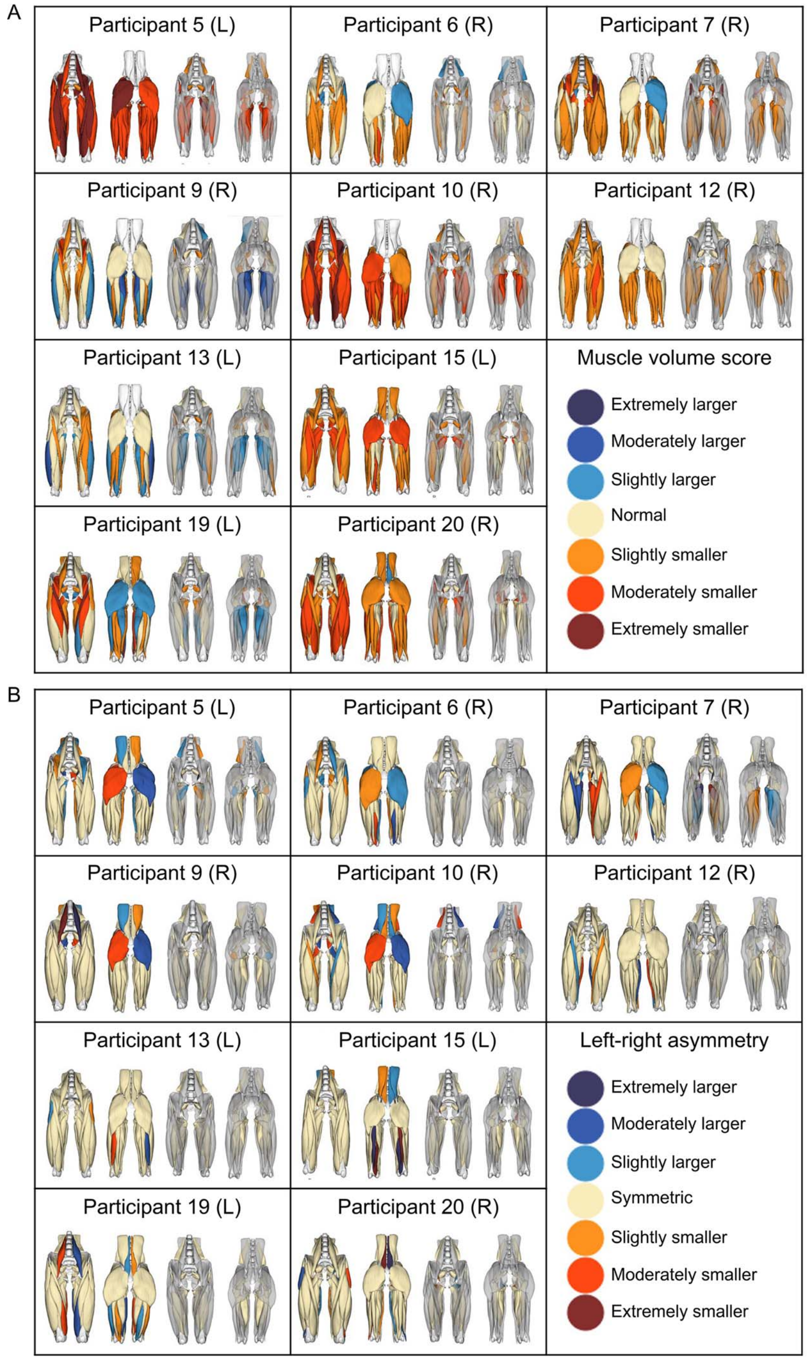


**Figure 1. Anterior and posterior views of superficial and deep muscle volumetric profiles and limb asymmetry in women with unilateral patellofemoral pain. L (left) or R (right) indicates the painful side. Tan indicates the average limb asymmetry percentage based on the normative data ±1 SD; orange/light blue, 1–2 SDs from the normal values; red/medium blue, 2–3 SDs from the normal values; and maroon/dark blue, ≥3 SDs from the normal values.**

difference in *z* scores between the pathological or worse limb and the contralateral limb. Muscle volumes within 1 SD were defined as the color tan, 1 to 2 SDs from the normal values as orange/light blue, 2 to 3 SDs from the normal values as red/medium blue, and 3+ SDs from the normal values as maroon/dark blue (Springbok Analytics Inc; Figures 1–4).

## Statistical Analysis

We did not carry out a priori power analysis because of the exploratory nature of the study. A post hoc power analysis was also not conducted, as it may have been conceptually flawed and analytically misleading.[17] Descriptive statistics were calculated for participant characteristics and lower extremity muscle volumes. Muscles were segmented using custom MATLAB (The Mathworks Inc) software via an automated procedure to minimize potential bias as previously described.[15] The comparison between automatic and manual segmentations has demonstrated good-to-excellent validity, with the automatic segmentation showing superior interobserver variability for most muscles.[15] Data processing in MATLAB was adapted from the methods described



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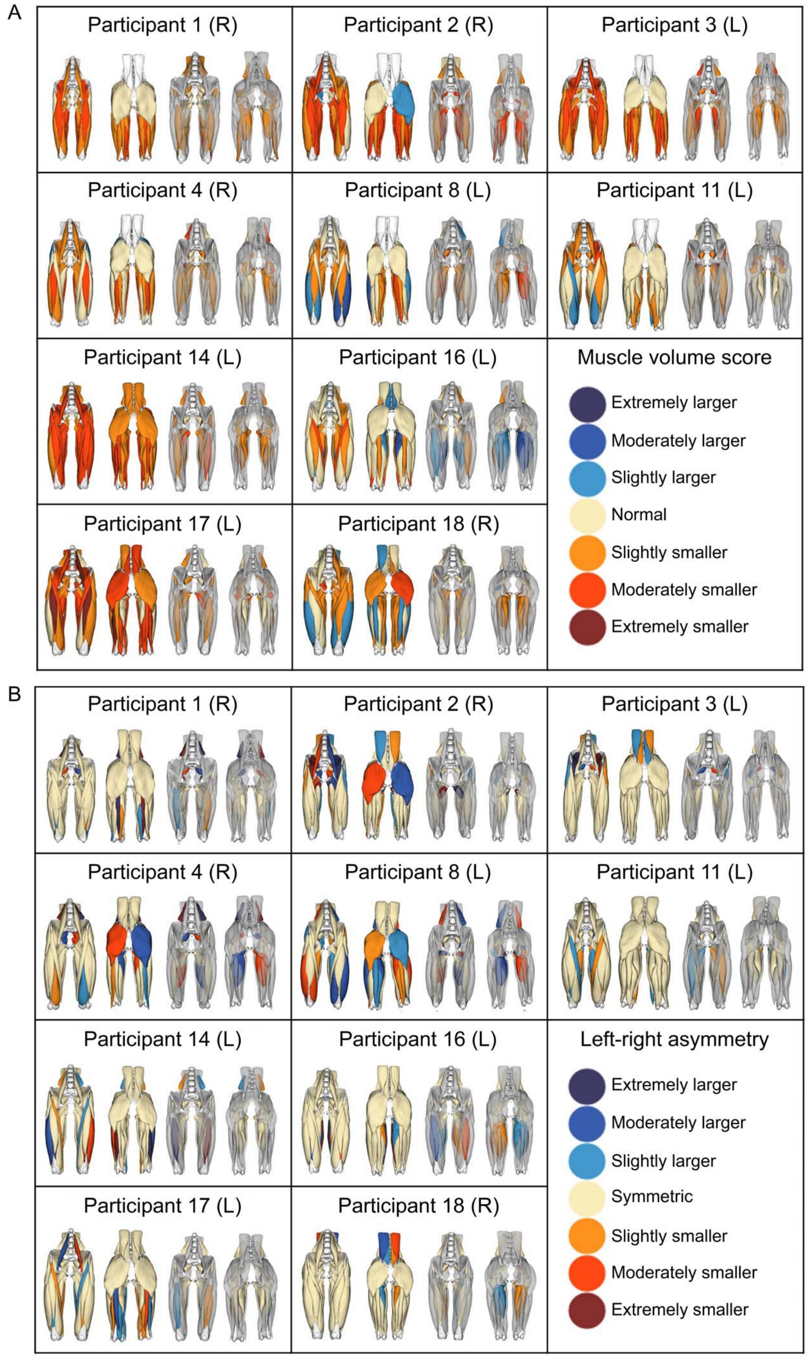


**Figure 2. Anterior and posterior views of superficial and deep muscle volumetric profiles and limb asymmetry in women with bilateral patellofemoral pain. L (left) or R (right) indicates the painful side. Tan indicates the average limb asymmetry percentage based on the normative data ±1 SD; orange/light blue, 1–2 SDs from the normal values; red/medium blue, 2–3 SDs from the normal values; and maroon/dark blue, ≥3 SDs from the normal values.**

by Ni et al.[15] Normalized muscle volumes (in $cm^3/kg \cdot m$) in the unilateral and bilateral PFP groups were compared with the normative database comprising a single limb from 8 women without pain.[9] Two separate 1-way analyses of variance were performed to compare muscle volumes among groups: (1) unilateral PFP (painful versus nonpainful limb) versus pain-free control and (2) bilateral PFP (more painful versus less painful limb) versus pain-free control. Independent *t* tests were also performed to compare muscle volumes between the unilateral (painful limb) and bilateral (more painful limb) groups. The $\alpha$ level was set a priori at .05. To determine clinical importance, we calculated Cohen *d* effect sizes with 95% CIs. Effect sizes were interpreted as *trivial* (<0.20), *small* (0.20–0.49), *moderate* (0.50–0.79), or *large* (≥0.80).[3] All calculations were performed using Microsoft Excel 2018 (Microsoft Corp).

## RESULTS

All 20 participants enrolled from the university setting completed the testing procedures. Descriptive data are reported in Table 1.



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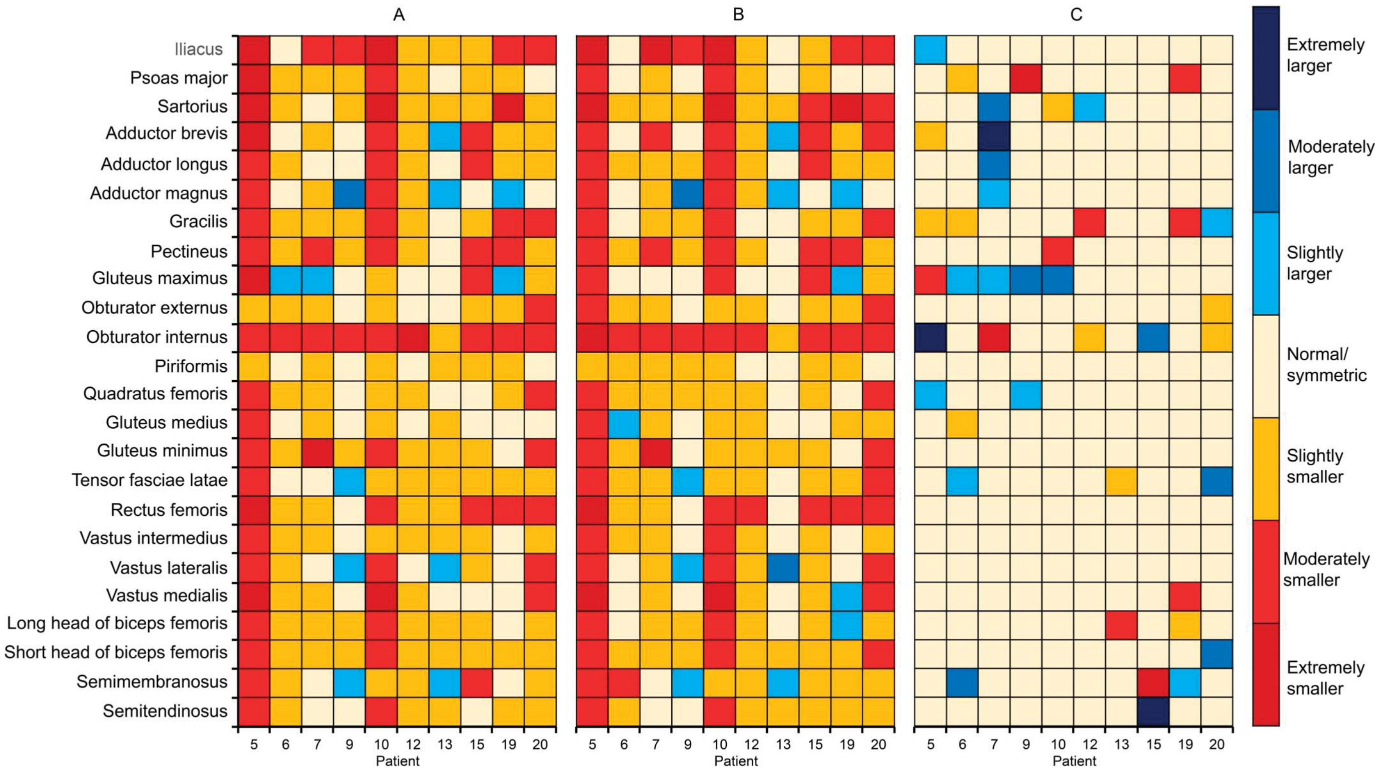


**Figure 3. Heatmap showing the distribution of *z* scores for muscle volume and limb asymmetry in women with unilateral patellofemoral pain. Muscle volume between A, the painful limb and pain-free control and B, the nonpainful limb and pain-free control. C, Limb asymmetry between the painful and nonpainful limbs. The numbers indicate those assigned to each participant. Tan indicates the average limb asymmetry percentage based on the normative data ±1 SD; orange/light blue, 1–2 SDs from the normal values; red/medium blue, 2–3 SDs from the normal values; and maroon/dark blue, ≥3 SDs from the normal values.**

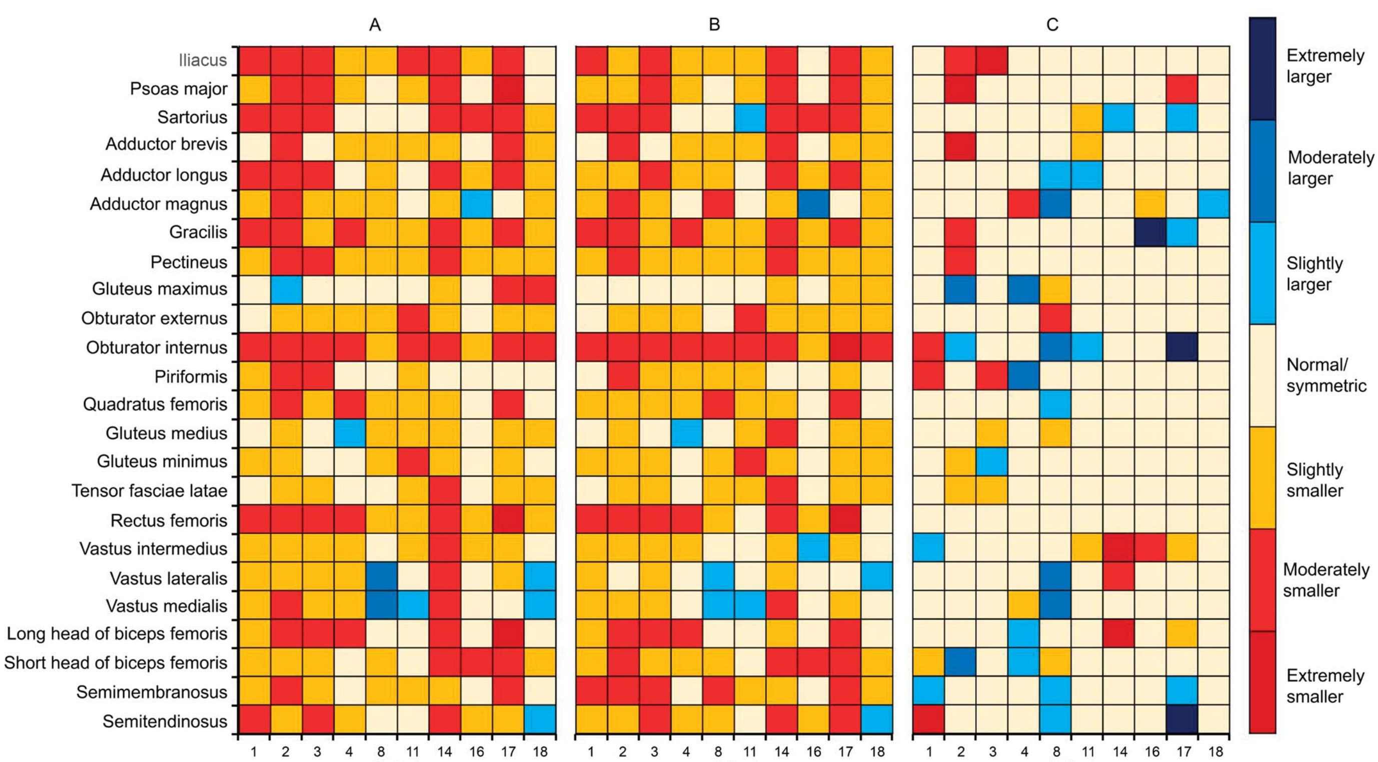


**Figure 4. Heatmap showing the distribution of *z* scores for muscle volume and limb asymmetry in women with bilateral patellofemoral pain. Muscle volume between A, the more painful limb and pain-free control and B, the less painful limb and pain-free control. C, Limb asymmetry between the more and less painful limbs. The numbers indicate those assigned to each participant. Tan indicates the average limb asymmetry percentage based on the normative data ±1 SD; orange/light blue, 1–2 SDs from the normal values; red/medium blue, 2–3 SDs from the normal values; and maroon/dark blue, ≥3 SDs from the normal values.**



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Table 1. Descriptive Data

| Characteristic or Self-Reported Measure | Unilateral PFP (n = 10) | Bilateral PFP (n = 10) | Pain-Free (n = 8) | P Value[a] |
|---|---|---|---|---|
| | No. | | | |
| Characteristic | | | | |
| Painful or more painful limb, right/left | 7/3 | 4/6 | NA | NC |
| Dominant limb, right/left | 10/0 | 8/2 | NA | NC |
| | Mean ± SD | | | |
| Age, y | 21.2 ± 4.9 | 25.8 ± 3.1 | 25.8 ± 8.8 | .15 |
| Height, cm | 163.3 ± 7.4 | 166.6 ± 8.4 | 168.5 ± 6.0 | .33 |
| Mass, kg | 63.9 ± 16.1 | 60.7 ± 7.5 | 62.7 ± 7.1 | .82 |
| Body mass index, kg/m$^2$ | 23.8 ± 5.0 | 21.9 ± 2.4 | 22.0 ± 2.0 | .42 |
| Self-reported measure | | | | |
| Symptom duration, mo | 27.6 ± 31.5 | 44.3 ± 64.7 | NA | .47 |
| Worst pain in the previous week (VAS), cm | 6.2 ± 1.5 | 5.7 ± 1.6 | NA | .48 |
| Anterior Knee Pain Scale | 71.6 ± 5.5 | 76.5 ± 6.1 | NA | .08 |
| Knee Injury and Osteoarthritis Outcome Score | | | | |
| Total (range, 0–100) | 66.7 ± 15.2 | 68.8 ± 13.5 | NA | .78 |
| Pain (range, 0–100) | 70.0 ± 19.4 | 70.7 ± 12.6 | NA | .92 |
| Symptoms (range, 0–100) | 73.8 ± 11.5 | 75.4 ± 14.5 | NA | .79 |
| Activities of Daily Living (range, 0–100) | 78.5 ± 23.1 | 81.6 ± 13.0 | NA | .72 |
| Sport and Recreation (range, 0–100) | 57.0 ± 22.3 | 59.5 ± 20.7 | NA | .80 |
| Quality of Life (range, 0–100) | 53.9 ± 15.1 | 57.1 ± 15.8 | NA | .65 |
| Patellofemoral (range, 0–100) | 58.4 ± 17.8 | 60.0 ± 20.1 | NA | .85 |
| Pain Self-Efficacy Questionnaire (range, 0–60) | 45.7 ± 8.9 | 50.6 ± 7.9 | NA | .21 |
| Pain Catastrophizing Scale (range, 0–52) | 11.6 ± 9.3 | 13.9 ± 7.0 | NA | .54 |

Abbreviations: PFP, patellofemoral pain; NA, not available; NC, not calculated; VAS, visual analog scale.
[a] P values were calculated for characteristics using a 1-way analysis of variance and for self-reported measures using an independent t test.

## Unilateral and Bilateral PFP Versus Pain-Free Control

Compared with the pain-free group, both the unilateral and bilateral PFP groups had bilaterally smaller volumes of the anterior (iliacus: $P \leq .0004$; $d$ range, 2.12–2.65), medial (adductor brevis, adductor longus, gracilis, and pectineus: $P \leq .02$; $d$ range, 1.25–2.48), posterior (obturator externus, obturator internus, and quadratus femoris: $P < .05$; $d$ range, 1.17–4.82), and lateral (gluteus minimus: $P \leq .03$; $d$ range, 1.16–2.09) hip muscles and knee extensors (rectus femoris: $P \leq .003$, $d$ range, 1.67–2.16) and flexors (long and short heads of the biceps femoris: $P \leq .01$; $d$ range, 1.56–1.93); however, we observed no differences in the muscle volumes of the adductor magnus, gluteus maximus, gluteus medius, vastus lateralis, and vastus medialis ($P > .05$; Tables 2 and 3).

We found that individual muscle volumes ranged from moderately larger to extremely smaller in both the unilateral (Figures 1 and 3) and bilateral (+Figures 2 and 4) PFP groups. Compared with the pain-free control group, (1) 30% to 100% of the unilateral PFP group and 30% to 100% of the bilateral PFP group had slightly smaller to extremely smaller muscle volumes in the hip muscles in both limbs and (2) 50% to 100% of the unilateral PFP group and 30% to 80% of the bilateral PFP group had slightly smaller to extremely smaller muscle volumes in the knee muscles in both limbs.

## Limb Asymmetry in Unilateral and Bilateral PFP

We found that limb asymmetry for individual muscle volumes ranged from extremely larger to extremely smaller in both the unilateral (Figures 1 and 3) and bilateral (Figures 2 and 4) PFP groups. Based on the $z$ scores, (1) up to 40% of the unilateral PFP group (50%–100% symmetric) and up to 20% of the bilateral PFP group (50%–90% symmetric) had slightly smaller to extremely smaller limb asymmetry in the hip muscles and (2) up to 20% of the unilateral PFP group (70%–100% symmetric) and up to 40% of the bilateral PFP group (50%–100% symmetric) had slightly smaller to extremely smaller limb asymmetry in the knee muscles.

## Unilateral Versus Bilateral PFP

We observed no differences in muscle volumes between the painful limb of the unilateral PFP group and the more painful limb of the bilateral PFP group ($P > .05$; Table 4).

## DISCUSSION

Women with PFP, regardless of unilateral or bilateral pain, have many muscles that are smaller bilaterally than those of pain-free women (Tables 2 and 3). Both the unilateral and bilateral PFP groups displayed inconsistent patterns and heterogeneous volumetric profiles of individual hip and knee muscles in the bilateral lower extremities (Figures 1–4). We also found no differences in muscle volumes between the painful limb in the unilateral PFP group and the more painful limb in the bilateral PFP group (Table 4), suggesting a similar magnitude of volumetric reduction existed between subgroups.

In their systematic review, Nascimento et al suggested that a combination of hip- and knee-muscle rehabilitation leads to greater benefits in pain relief and function versus knee-muscle rehabilitation alone, indicating that understanding hip muscles is critical in PFP management.[18] However, most previous studies, in which authors measured muscle volumes

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Table 2. **Comparison of Lower Extremity Muscle Volume Between Women With Unilateral PFP and Pain-Free Women**

| Variable | Group, Mean ± SD, cm³/kg·m | | | | |
|---|---|---|---|---|---|
| | Unilateral PFP | | | Cohen *d* Effect Size (95% CI) | |
| | Painful Limb (n = 10) | Nonpainful Limb (n = 10) | Pain-Free Limb (n = 8) | Painful Limb Versus Pain-Free Limb | Nonpainful Limb Versus Pain-Free Limb |
| Anterior hip muscles | | | | | |
| Iliacus | 1.04 ± 0.24[a] | 1.04 ± 0.21[a] | 1.49 ± 0.17 | 2.12 (0.88, 3.16) | 2.33 (1.04, 3.39) |
| Psoas major | 1.74 ± 0.35 | 1.85 ± 0.39 | 2.15 ± 0.45 | 1.03 (0.00, 1.97) | 0.72 (–0.27, 1.64) |
| Sartorius | 0.94 ± 0.25[a] | 0.93 ± 0.22[a] | 1.24 ± 0.16 | 1.39 (0.30, 2.35) | 1.58 (0.45, 2.56) |
| Medial hip muscles | | | | | |
| Adductor brevis | 0.68 ± 0.18[a] | 0.66 ± 0.18[a] | 0.92 ± 0.15 | 1.43 (0.33, 2.40) | 1.55 (0.43, 2.53) |
| Adductor longus | 1.01 ± 0.21[a] | 0.99 ± 0.19[a] | 1.36 ± 0.22 | 1.63 (0.50, 2.61) | 1.82 (0.64, 2.82) |
| Adductor magnus | 4.40 ± 1.00 | 4.42 ± 1.21 | 4.47 ± 0.67 | 0.08 (–0.85, 1.01) | 0.05 (–0.88, 0.98) |
| Gracilis | 0.62 ± 0.12[a] | 0.65 ± 0.16[a] | 0.85 ± 0.16 | 1.66 (0.51, 2.64) | 1.25 (0.18, 2.20) |
| Pectineus | 0.32 ± 0.09[a] | 0.33 ± 0.09[a] | 0.54 ± 0.10 | 2.33 (1.04, 3.40) | 2.22 (0.96, 3.27) |
| Posterior hip muscles | | | | | |
| Gluteus maximus | 6.56 ± 1.02 | 6.30 ± 0.99 | 6.90 ± 0.79 | 0.37 (–0.59, 1.29) | 0.66 (–0.32, 1.58) |
| Obturator externus | 0.36 ± 0.09[a] | 0.35 ± 0.08[a] | 0.46 ± 0.08 | 1.17 (0.11, 2.11) | 1.38 (0.29, 2.33) |
| Obturator internus | 0.09 ± 0.03[a] | 0.11 ± 0.02[a] | 0.23 ± 0.03 | 4.67 (2.72, 6.17) | 4.82 (2.83, 6.36) |
| Piriformis | 0.30 ± 0.06 | 0.28 ± 0.06[a] | 0.39 ± 0.12 | 0.99 (–0.04, 1.92) | 1.21 (0.15, 2.15) |
| Quadratus femoris | 0.19 ± 0.05[a] | 0.19 ± 0.05[a] | 0.29 ± 0.06 | 1.83 (0.65, 2.83) | 1.83 (0.65, 2.83) |
| Lateral hip muscles | | | | | |
| Gluteus medius | 2.44 ± 0.34 | 2.35 ± 0.45 | 2.81 ± 0.39 | 1.02 (–0.01, 1.95) | 1.08 (0.04, 2.02) |
| Gluteus minimus | 0.62 ± 0.12[a] | 0.64 ± 0.14[a] | 0.90 ± 0.15 | 2.09 (0.86, 3.13) | 1.80 (0.63, 2.80) |
| Tensor fasciae latae | 0.42 ± 0.14 | 0.38 ± 0.12[a] | 0.56 ± 0.18 | 0.88 (–0.13, 1.81) | 1.21 (0.15, 2.15) |
| Knee extensors | | | | | |
| Rectus femoris | 1.67 ± 0.36[a] | 1.61 ± 0.32[a] | 2.23 ± 0.30 | 1.67 (0.53, 2.66) | 1.92 (0.72, 2.93) |
| Vastus intermedius | 1.71 ± 0.28[a] | 1.66 ± 0.34[a] | 2.12 ± 0.21 | 1.63 (0.49, 2.61) | 1.58 (0.46, 2.56) |
| Vastus lateralis | 6.15 ± 1.15 | 6.12 ± 1.11 | 6.79 ± 0.84 | 0.62 (–0.36, 1.54) | 0.67 (–0.32, 1.59) |
| Vastus medialis | 2.88 ± 0.56 | 3.02 ± 0.68 | 3.40 ± 0.35 | 1.08 (0.04, 2.02) | 0.68 (–0.31, 1.60) |
| Knee flexors | | | | | |
| Biceps femoris long head | 1.38 ± 0.22[a] | 1.38 ± 0.24[a] | 1.77 ± 0.20 | 1.84 (0.66, 2.85) | 1.75 (0.59, 2.74) |
| Biceps femoris short head | 0.53 ± 0.13[a] | 0.50 ± 0.13[a] | 0.74 ± 0.14 | 1.56 (0.44, 2.54) | 1.78 (0.62, 2.78) |
| Semimembranosus | 1.85 ± 0.34 | 1.73 ± 0.36 | 2.10 ± 0.29 | 0.78 (–0.22, 1.71) | 1.12 (0.07, 2.06) |
| Semitendinosus | 1.19 ± 0.25 | 1.21 ± 0.24 | 1.47 ± 0.25 | 1.12 (0.07, 2.06) | 1.06 (0.03, 2.00) |

Abbreviation: PFP, patellofemoral pain.
[a] Different from pain-free women ($P < .05$).

in the population with PFP, have been largely limited to small portions of the quadriceps, which cannot provide a comprehensive understanding of the specific characteristics of PFP.[6,19–22] Our findings of smaller volumes in hip and knee muscles support the need for a comprehensive examination of both hip and knee musculature when evaluating individuals with PFP.

We found bilaterally smaller muscle volumes in the lower extremity in the unilateral PFP group, which is in line with previous findings of bilateral neuromuscular dysfunction in patients with unilateral PFP.[11,12] Our results for muscle volumes of the vastus lateralis and vastus medialis were also consistent with those of a recent investigation.[19] Kaya et al found that the volume of the quadriceps femoris measured using MRI was smaller on the painful than nonpainful side.[22] However, they did not include a control group, preventing a direct comparison with our findings. Even though little is known about the volumetric profile in bilateral limbs in PFP cohorts, our data may be supported by the observations of bilateral volumetric deficits assessed using MRI in other knee pathologies (eg, anterior cruciate ligament injury, meniscus tear, and knee osteoarthritis).[8,23] Although the exact mechanisms of contralateral changes are still not clarified, a bilateral damping effect of the central nervous system responding to unilateral pain has been suggested.[24,25]

Another possible mechanism is a reduction in physical activity due to pain and disability. Reduced physical activity is associated with decreased lower extremity muscle volume.[26] Individuals with PFP performed fewer daily steps and less activity intensity versus pain-free counterparts.[3] Although we did not collect physical activity data, our PFP cohort displayed lower mean scores on the Activities of Daily Living (unilateral PFP: 78.5; bilateral PFP: 81.6) and Sport and Recreation (unilateral PFP: 57.0; bilateral PFP: 59.5) subscales of the KOOS. Given that lower scores on those subscales are associated with lower self-reported physical activity levels, our participants with PFP might have reduced activity engagement.[27] Still, investigators should conduct prospective studies to assess whether a direct association exists between decreased activity levels and reduced muscle volume in PFP cohorts.

Our findings revealed that both the unilateral and bilateral PFP groups exhibited overall inconsistent volumetric patterns across individual muscles compared with the pain-free control group, which agrees with previous data.[7] We found that only 1 muscle, the obturator internus, was consistently smaller among all individual women with unilateral or bilateral PFP than in pain-free women. The inconsistent observation across the participants indicates heterogeneous volumetric profiles of the lower extremity muscles across women with PFP.[7] Regarding limb asymmetry, >50% of women with unilateral and those with bilateral PFP showed symmetric profiles across the muscles assessed, supporting a tendency of similar extent of bilaterally smaller muscle volumes. Evidence of bilaterally smaller muscle

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Table 3. Comparison of Lower Extremity Muscle Volume Between Women With Bilateral PFP and Pain-Free Women

| Variable | Group, Mean ± SD, cm³/kg·m: Bilateral PFP, More Painful Limb (n = 10) | Bilateral PFP, Less Painful Limb (n = 10) | Pain-Free (n = 8) | Cohen *d* Effect Size (95% CI): More Painful Limb Versus Pain-Free | Less Painful Limb Versus Pain-Free |
|---|---|---|---|---|---|
| Anterior hip muscles | | | | | |
| Iliacus | 1.10 ± 0.17[a] | 1.04 ± 0.17[a] | 1.49 ± 0.17 | 2.29 (1.01, 3.36) | 2.65 (1.28, 3.76) |
| Psoas major | 1.66 ± 0.33[a] | 1.66 ± 0.36[a] | 2.15 ± 0.45 | 1.27 (0.20, 2.22) | 1.22 (0.16, 2.17) |
| Sartorius | 1.01 ± 0.28 | 1.01 ± 0.26 | 1.24 ± 0.16 | 0.98 (–0.05, 1.91) | 1.04 (0.00, 1.97) |
| Medial hip muscles | | | | | |
| Adductor brevis | 0.73 ± 0.09[a] | 0.71 ± 0.10[a] | 0.92 ± 0.15 | 1.58 (0.46, 2.56) | 1.69 (0.54, 2.68) |
| Adductor longus | 0.94 ± 0.17[a] | 0.97 ± 0.20[a] | 1.36 ± 0.22 | 2.17 (0.92, 3.22) | 1.87 (0.68, 2.87) |
| Adductor magnus | 3.94 ± 0.84 | 4.13 ± 0.55 | 4.47 ± 0.67 | 0.69 (–0.30, 1.61) | 0.56 (–0.41, 1.48) |
| Gracilis | 0.55 ± 0.11[a] | 0.59 ± 0.12[a] | 0.85 ± 0.16 | 2.24 (0.97, 3.29) | 1.87 (0.69, 2.88) |
| Pectineus | 0.36 ± 0.04[a] | 0.36 ± 0.05[a] | 0.54 ± 0.10 | 2.48 (1.15, 3.57) | 2.37 (1.07, 3.44) |
| Posterior hip muscles | | | | | |
| Gluteus maximus | 6.52 ± 0.66 | 6.29 ± 0.51 | 6.90 ± 0.79 | 0.53 (–0.44, 1.45) | 0.94 (–0.08, 1.87) |
| Obturator externus | 0.34 ± 0.07[a] | 0.32 ± 0.05[a] | 0.46 ± 0.08 | 1.61 (0.48, 2.59) | 2.16 (0.91, 3.20) |
| Obturator internus | 0.10 ± 0.03[a] | 0.11 ± 0.02[a] | 0.23 ± 0.03 | 4.33 (2.49, 5.76) | 4.82 (2.83, 6.36) |
| Piriformis | 0.29 ± 0.06 | 0.28 ± 0.08[a] | 0.39 ± 0.12 | 1.10 (0.05, 2.03) | 1.11 (0.06, 2.04) |
| Quadratus femoris | 0.17 ± 0.04[a] | 0.19 ± 0.04[a] | 0.29 ± 0.06 | 2.41 (1.10, 3.49) | 2.01 (0.79, 3.03) |
| Lateral hip muscles | | | | | |
| Gluteus medius | 2.50 ± 0.40 | 2.38 ± 0.34 | 2.81 ± 0.39 | 0.78 (–0.21, 1.71) | 1.19 (0.13, 2.13) |
| Gluteus minimus | 0.70 ± 0.08[a] | 0.75 ± 0.11[a] | 0.90 ± 0.15 | 1.72 (0.57, 2.72) | 1.16 (0.11, 2.10) |
| Tensor fasciae latae | 0.42 ± 0.09 | 0.41 ± 0.10[a] | 0.56 ± 0.18 | 1.02 (–0.01, 1.96) | 1.07 (0.03, 2.00) |
| Knee extensors | | | | | |
| Rectus femoris | 1.67 ± 0.31[a] | 1.57 ± 0.31[a] | 2.23 ± 0.30 | 1.83 (0.65, 2.84) | 2.16 (0.91, 3.20) |
| Vastus intermedius | 1.91 ± 0.30 | 1.69 ± 0.32[a] | 2.12 ± 0.21 | 0.79 (–0.21, 1.72) | 1.55 (0.43, 2.52) |
| Vastus lateralis | 6.43 ± 0.73 | 6.52 ± 1.11 | 6.79 ± 0.84 | 0.46 (–0.50, 1.38) | 0.27 (–0.68, 1.19) |
| Vastus medialis | 3.20 ± 0.49 | 3.40 ± 0.60 | 3.40 ± 0.35 | 0.46 (–0.50, 1.38) | 0.00 (–0.93, 0.93) |
| Knee flexors | | | | | |
| Biceps femoris long head | 1.39 ± 0.26[a] | 1.32 ± 0.28[a] | 1.77 ± 0.20 | 1.61 (0.48, 2.59) | 1.81 (0.64, 2.81) |
| Biceps femoris short head | 0.53 ± 0.12[a] | 0.51 ± 0.10[a] | 0.74 ± 0.14 | 1.63 (0.49, 2.61) | 1.93 (0.73, 2.94) |
| Semimembranosus | 1.65 ± 0.26[a] | 1.70 ± 0.25[a] | 2.10 ± 0.29 | 1.65 (0.51, 2.63) | 1.49 (0.38, 2.46) |
| Semitendinosus | 1.11 ± 0.29[a] | 1.18 ± 0.29 | 1.47 ± 0.25 | 1.32 (0.24, 2.27) | 1.06 (0.02, 2.00) |

Abbreviation: PFP, patellofemoral pain.

[a] Different from pain-free women ($P < .05$).

volumes in women with unilateral PFP suggests that the pain-free limb should not be deemed as the normal reference when initially evaluating their baseline values and estimating the extent of restoration in patients with unilateral PFP.[11,12] Clinicians should be aware that some women with PFP may exhibit bilateral muscle involvement that is relatively balanced in volume.

Identifying the specific affected superficial and deeper muscles aids in providing more targeted exercises. Although the muscle volume of superficial muscles may be more apparent, the muscle volume of deeper muscles can be subtle and challenging to target. We acknowledge the high cost and challenges of specialized imaging techniques in clinical settings; however, our data demonstrated deeper hip muscles should be a focus when developing rehabilitation programs for patients with PFP. Deeper muscles are deemed important stabilizers and play an essential role in maintaining body posture and stabilizing joint movements during functional tasks.[28] Souza et al suggested that the poor control of excessive internal femoral rotation could be linked to abnormal patellofemoral joint kinematics in women.[29] We also observed smaller muscle volumes of multiple deeper muscles, such as the obturator externus, obturator internus, gluteus minimus, and quadratus femoris, which attach to the femur and stabilize or externally rotate the hip joint. However, it is still unclear how those deeper muscles contribute to patellofemoral joint kinematics and stress in the population with PFP. Future research is needed to identify if smaller, deeper, and larger global muscles also contribute to patellofemoral joint kinematics and stress.

We did not observe differences in the muscle volumes of the gluteus maximus, gluteus medius, vastus lateralis, and vastus medialis in the unilateral and bilateral PFP groups compared with the pain-free control group. These results were somewhat surprising, given that patients with PFP commonly have difficulty in the actions associated with these muscles.[2,5] Hip strength and rate of torque development are impaired in women with PFP without signs of altered gluteus maximus and medius muscle thickness assessed using ultrasound imaging.[30] One possible explanation is that neuromuscular dysfunction in people with PFP without a lack of muscle volume could be attributable to muscle inhibition via neural mechanisms. Although not all individuals with PFP present with inhibition of the gluteal muscles, investigators should determine the association between muscle volume and other neuromuscular functions to guide a better rehabilitation direction for this chronic knee condition.[31] Our results for the vastus lateralis and vastus medialis are supported by those of a previous report demonstrating no difference in normalized quadriceps muscle volume between women with PFP and pain-free women; however, differences in measurement technique and volumetric calculations limit our ability to make direct comparisons between studies.[19]

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**Table 4. Comparison of Lower Extremity Muscle Volume Between Women With Unilateral (Painful Limb) and Bilateral (More Painful Limb) PFP**

| Variable | Group, Mean ± SD, cm³/kg·m: Unilateral PFP, Painful Limb (n = 10) | Bilateral PFP, More Painful Limb (n = 10) | Cohen *d* Effect Size (95% CI) |
|---|---|---|---|
| Anterior hip muscles | | | |
| Iliacus | 1.04 ± 0.24 | 1.10 ± 0.17 | 0.29 (–0.60, 1.16) |
| Psoas major | 1.74 ± 0.35 | 1.66 ± 0.33 | 0.24 (–0.65, 1.10) |
| Sartorius | 0.94 ± 0.25 | 1.01 ± 0.28 | 0.26 (–0.63, 1.13) |
| Medial hip muscles | | | |
| Adductor brevis | 0.68 ± 0.18 | 0.73 ± 0.09 | 0.35 (–0.55, 1.22) |
| Adductor longus | 1.01 ± 0.21 | 0.94 ± 0.17 | 0.37 (–0.53, 1.23) |
| Adductor magnus | 4.40 ± 1.00 | 3.94 ± 0.84 | 0.50 (–0.41, 1.37) |
| Gracilis | 0.62 ± 0.12 | 0.55 ± 0.11 | 0.61 (–0.31, 1.48) |
| Pectineus | 0.32 ± 0.09 | 0.36 ± 0.04 | 0.57 (–0.34, 1.44) |
| Posterior hip muscles | | | |
| Gluteus maximus | 6.56 ± 1.02 | 6.52 ± 0.66 | 0.05 (–0.83, 0.92) |
| Obturator externus | 0.36 ± 0.09 | 0.34 ± 0.07 | 0.25 (–0.64, 1.12) |
| Obturator internus | 0.09 ± 0.03 | 0.10 ± 0.03 | 0.33 (–0.56, 1.20) |
| Piriformis | 0.30 ± 0.06 | 0.29 ± 0.06 | 0.17 (–0.72, 1.04) |
| Quadratus femoris | 0.19 ± 0.05 | 0.17 ± 0.04 | 0.44 (–0.46, 1.31) |
| Lateral hip muscles | | | |
| Gluteus medius | 2.44 ± 0.34 | 2.50 ± 0.40 | 0.16 (–0.72, 1.03) |
| Gluteus minimus | 0.62 ± 0.12 | 0.70 ± 0.08 | 0.78 (–0.16, 1.66) |
| Tensor fasciae latae | 0.42 ± 0.14 | 0.42 ± 0.09 | 0.00 (–0.88, 0.88) |
| Knee extensors | | | |
| Rectus femoris | 1.67 ± 0.36 | 1.67 ± 0.31 | 0.00 (–0.88, 0.88) |
| Vastus intermedius | 1.71 ± 0.28 | 1.91 ± 0.30 | 0.69 (–0.24, 1.56) |
| Vastus lateralis | 6.15 ± 1.15 | 6.43 ± 0.73 | 0.29 (–0.60, 1.16) |
| Vastus medialis | 2.88 ± 0.56 | 3.20 ± 0.49 | 0.61 (–0.31, 1.48) |
| Knee flexors | | | |
| Biceps femoris long head | 1.38 ± 0.22 | 1.39 ± 0.26 | 0.04 (–0.84, 0.92) |
| Biceps femoris short head | 0.53 ± 0.13 | 0.53 ± 0.12 | 0.00 (–0.88, 0.88) |
| Semimembranosus | 1.85 ± 0.34 | 1.65 ± 0.26 | 0.66 (–0.27, 1.53) |
| Semitendinosus | 1.19 ± 0.25 | 1.11 ± 0.29 | 0.30 (–0.60, 1.16) |

Abbreviation: PFP, patellofemoral pain.

## LIMITATIONS

This study had limitations. We cannot generalize our findings to men, adolescents, or older adults with PFP because we only analyzed women aged 18 to 35 years. Future investigations are needed to explore the influence of activity levels on muscle volume in women with PFP. We found heterogeneous volumetric profiles across our participants, which may be due to the relatively small number of individuals in each group when they were dichotomized into unilateral and bilateral PFP. Researchers should conduct an a priori power analysis to ensure the sample size will yield adequate power to detect statistical differences. Future prospective studies should also be done to determine whether a reduction in lower extremity muscle volume is a risk factor for or a consequence of PFP. Although our MRI technique is supported by Ni et al, they did not mention reliability, warranting future studies.[15] Lastly, although we compared our samples with demographically similar pain-free counterparts in terms of sex, age, height, mass, and body mass index, researchers should exercise caution when using normative databases with incomplete specifications, particularly regarding other potential confounding factors, such as the proportion of dominant limb and physical activity level.[9]

## CLINICAL IMPLICATIONS

Our findings emphasize the need to consider evaluating and managing bilateral hip and knee muscle volumes in women with PFP. Rehabilitative approaches could be enhanced through the integration of exercise protocols targeting hypertrophy (eg, eccentric exercise) of the hip and knee musculature as a whole, potentially yielding therapeutic benefits for affected individuals.[32] In addition, the observed inconsistent and heterogeneous volumetric profiles among our participants highlight the importance of implementing evidence-based intervention approaches that can be personalized for individuals with PFP. Clinicians should also note that the muscle volumes in the gluteus maximus, gluteus medius, vastus lateralis, and vastus medialis, typically considered weak in individuals with PFP, were not smaller in women with PFP than pain-free women. The effectiveness of rehabilitation programs in targeting individualized smaller muscles remains uncertain and focusing solely on improving muscle function may not be the most effective strategy for addressing PFP. Hence, a multifaceted treatment approach (eg, load management and movement and gait retraining strategies) should be simultaneously considered for better outcomes.[33,34]

## CONCLUSIONS

Both women with unilateral and those with bilateral PFP may experience smaller muscle volumes of multiple muscles in both limbs than pain-free women. These bilateral alterations suggest that authors of future studies should include a control group to enable a more accurate comparison. Clinicians should consider incorporating evidence-based exercises targeting bilateral muscles in the lower extremity when treating women with unilateral and those with bilateral PFP. Inconsistent patterns and heterogeneous volumetric profiles of our cohort samples may suggest that personalized evaluation and intervention are warranted for this challenging orthopaedic condition; however, cluster analysis with larger cohorts for unilateral and bilateral PFP subgroups is warranted.


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