

Comparison of Gluteus Medius Muscle Activation in Women With and Without Patellofemoral Pain

Michelle N. Samuel, PhD, ATC*; Szu-Ping Lee, PhD, PT†; Andrew Hooyman, PhD GStat‡; Kevin C. Miller, PhD, ATC§; Daniel L. Young, PhD, DPT, PT†; Neal R. Glaviano, PhD, ATC||

Departments of *Kinesiology and Nutrition Sciences and †Physical Therapy, University of Nevada, Las Vegas; ‡Department of Physical Therapy, Chapman University, Irvine, CA; §Department of Health and Human Performance, Texas State University, San Marcos; ||Department of Kinesiology, University of Connecticut, Storrs

Context: Women with patellofemoral pain (PFP) commonly have hip muscle weakness in comparison with women without PFP. One underlying mechanism for this muscle weakness is inhibition. Although the presence of muscle weakness is well documented in women with PFP, few authors have investigated gluteus medius inhibition in this population. Women are twice as likely to suffer from PFP when compared with men; therefore, we focused on the female population.

Objective: To compare voluntary activation of the gluteus medius between women with and without PFP.

Design: Case-control study.

Setting: Laboratory.

Patients or Other Participants: Twenty-eight female participants: 13 pain-free control participants (age = 21.6 ± 3.6 years, height = 1.66 ± 0.06 m, mass = 65.4 ± 11.3 kg) and 15 participants with PFP (age = 22.3 ± 3.2 years, height = 1.66 ± 0.07 m, mass = 75.3 ± 22.6 kg, duration of pain = 3.5–96 months).

Main Outcome Measure(s): Standing hip-abduction normalized strength (N·m/kg), superimposed-burst force, and gluteus

medius central activation ratio (CAR). Linear modeling was used to compare forces and the CAR between groups while controlling for age, mass, and hip-abduction force.

Results: Women with PFP had lower gluteus medius CAR than controls. Overall, after controlling for participant age, mass, and gluteus medius maximal voluntary isometric contraction, the PFP group had an average gluteus medius CAR 2.5% lower than the pain-free control group (control = $98.4\% \pm 0.01\%$, PFP = $95.9\% \pm 0.65\%$, $P = .004$).

Conclusions: Women with PFP had reduced voluntary activation of the gluteus medius when assessed with a superimposed burst. Due to the wide range of CAR values found (74%–99%), inhibition was present in some of the participants. This provides evidence that assessment of gluteal voluntary activation could assist with targeted treatment programs for individuals presenting with PFP.

Key Words: anterior knee pain, inhibition, hip muscle, assessment

Key Points

- Women with patellofemoral pain had reduced activation of the gluteus medius muscle.
- Identifying the presence of inhibition may be useful for clinicians to determine the most appropriate treatment techniques.

Patellofemoral pain (PFP) affects as much as 7.3% of all patients who seek care from an orthopaedic physician in the United States.¹ Patellofemoral pain accounts for approximately 25% of all knee injuries among physically active populations,² and the prevalence of PFP in women is twice that in men.¹ Patellofemoral pain commonly presents as diffuse pain across the anterior knee that increases with activities such as running, squatting, and walking up and down stairs.³ The etiology of PFP is multifactorial, because numerous underlying factors are associated with development and progression of this condition, including but not limited to muscle weakness, abnormal motor activation patterns, abnormal joint kinematics, and abnormal joint stress.^{3–5}

Clinicians and researchers place a large focus on the gluteus medius in the evaluation and management of PFP. The gluteus medius is an important stabilizer muscle, functioning to maintain neutral alignment of the lower extremity in the frontal

plane during dynamic movement.⁶ To prevent excessive lower extremity malalignment in the frontal plane, adequate strength and activation of the gluteus medius are important. However, deficits in strength and activation are common in individuals with PFP.^{6–10} It has been theorized that abnormal gluteus medius muscle function is related to excessive hip adduction and internal rotation, causing dynamic knee valgus and contributing to the development of PFP.¹¹

Although current treatment strategies aim to improve hip musculature function, there are inconsistent findings in how these strategies lead to improved strength or movement patterns.^{12–14} The lack of improvements in strength or movement patterns for some individuals with PFP may imply additional underlying neuromuscular factors that should be considered in the evaluation and management of PFP. Therefore, it would be beneficial to investigate additional assessment tools that could detect specific deficits in hip function beyond strength and movement patterns.

One underlying explanation for abnormal gluteus medius activation in individuals with PFP could be related to muscle inhibition. An inhibited muscle is not capable of recruiting all available motor units, resulting in reduced force output. One suggested explanation for inhibition occurring in the gluteus medius is disrupted neural signaling transmission.¹⁵ This is suggested to occur when mechanoreceptors located inside the tissues of a strained joint are excessively activated, which in the case of PFP could be caused by excessive hip adduction. This heightened joint afference leads to an inhibitory response to the surrounding musculature, reducing its voluntary activation.¹⁵ The superimposed-burst (SIB) technique is commonly used to measure muscle voluntary activation and is quantified as the central activation ratio (CAR).^{16–18} The CAR indicates the level of voluntary activation of a specific muscle, ranging from 0% to 100%. Although the CAR is a valid and reliable measure in individuals with PFP, this has been limited to the quadriceps.^{16,17} Hart et al found that patients with anterior knee pain had 78.6% quadriceps inhibition and suggested this may lead to muscle weakness and kinematic changes.¹⁶ Researchers recently provided initial evidence that the CAR is a valid and reliable measure of gluteus medius and maximum activation in a healthy cohort.¹⁸ Gluteal CAR has been assessed in a small cross-sectional study but has not been compared directly with a healthy cohort.¹⁹ Determining the gluteal CAR for women with PFP could assist in investigating the lack of improvements in strength sometimes found after rehabilitative treatment. Therefore, the purpose of this study was to compare the gluteus medius CAR of women with and without PFP. We hypothesized that women with PFP would present with reduced CAR in comparison with the pain-free controls.

METHODS

The STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) checklist for case-control studies was used to assist in providing quality methodology.²⁰ In this case-control study, we compared group differences between women with PFP and pain-free controls. The independent variable was group (PFP, control). The dependent variables were CAR of the gluteus medius and maximal voluntary isometric contraction (MVIC) of the gluteus medius.

Participants

Twenty-eight female participants volunteered for this study: 13 pain-free controls and 15 with PFP. As an interinstitutional collaborative study, participants with PFP were collected from 2 universities and surrounding communities. Both the University of Nevada, Las Vegas, and University of Toledo obtained institutional review board approval. Before data collection, participants were screened for inclusion and exclusion criteria (Table 1) adhering to the International Patellofemoral Pain Consensus Statement.²¹ Once a participant's eligibility was confirmed, written informed consent was acquired. All participants with PFP were screened by a licensed athletic trainer with 10+ years of clinical experience to confirm diagnosis based on their symptoms. Any participant who reported PFP bilaterally was instructed to self-select their most symptomatic side to be used for testing.

Table 1. Inclusion and Exclusion Criteria

Inclusion: pain-free control
- Female, between 18 and 35 years old - Physically active: exercise 3 times per week for at least 30 minutes each time
Inclusion: PFP
- Female, between 18 and 35 years old - Physically active: exercise 3 times per week for at least 30 minutes each time - Insidious onset of anterior knee pain - Have retro-patellar pain for greater than 3 months - Have pain during 2 of the following activities: jumping, kneeling, running, squatting, stair ambulation, prolonged sitting, or contracting quadriceps
Exclusion (both groups)
- Lower extremity injuries (other than PFP) within the last 6 months - Previous lower extremity or low back surgery - History of patella subluxation or dislocation - Lower limb fracture - Concussion in the last 6 months - Knee ligamentous instability - Hypersensitivity to electrical stimulation - History of neurological impairments - Pregnancy

Abbreviation: PFP, patellofemoral pain.

Instrumentation

The gluteus medius CAR was calculated using the SIB technique.^{16–18} Isometric hip-abduction force was assessed with a Biodex System 3 Pro dynamometer (Biodex Multi-Joint System 3; Biodex Medical Systems, Inc). Force data points were obtained with a 16-bit acquisition system at 125 Hz (MP150; BIOPAC Systems, Inc).¹⁷ A sequence of manually delivered electrical stimuli was applied to perform the SIB with a Grass Stimulator S48 (Grass Technologies) and a stimulus-isolation unit (Grass Stimulator; Grass Technologies).

Procedures

Participants reported to the research laboratory for a single data collection session. For pain-free controls, the dominant extremity (ie, preferred leg to kick a ball) was chosen for testing.

During the session, 2 measures were collected: hip-abduction MVIC force (F_{MVIC}) and MVIC force with a SIB of electrical stimulation (F_{SIB}). Before testing, participants completed a 5-minute walking warm-up on a treadmill at their preferred walking speed with 0% incline. Then, two 5- × 9-cm adhesive electrodes (Axelguard) were placed over the participant's gluteus medius, with one placed directly inferior to the iliac crest and the second directly superior to the greater trochanter.¹⁸ Assessment of hip-abduction strength was performed with the participant in a standing position. The dynamometer axis of rotation was lined up with the anterior superior iliac spine while the arm of the dynamometer was attached to the leg approximately 5 cm proximal to the lateral femoral condyle. The Biodex chair was positioned to assist with stabilizing trunk motion. The chair height was adjusted so that a bolster placed on the chair would be at the level of the participant's contralateral hip to prevent trunk and pelvic motion (Figure 1). When testing was being completed, participants were instructed to stand up straight with their arms held across their chest.



Figure 1. Positioning of participant on the Biodex System 3 for hip abduction.

As described previously, to acclimate participants to the task, they performed a sequence of submaximal isometric contractions at 25%, 50%, and 75% of their self-determined maximal ability with a 1-minute rest between trials.¹⁸ Participants were instructed to perform these contractions by ramping up to the defined intensity and holding for 3 to 5 seconds. Participants were then instructed to perform 2 contractions of maximal effort, while also being given verbal feedback from the investigator and visual feedback on a computer monitor. The verbal and visual feedback were provided to encourage the participant to perform at true maximal effort. The visual feedback was a line graph representing the amount of force the participant was producing in real time. The participant then performed 6 MVICs with a superimposed electrical burst stimulation. The first 3 trials were performed with maximal contraction and with submaximal stimulus amplitude at 25%, 50%, and 75%. The last 3 trials were performed with a 100% SIB stimulation applied with a stimulus-isolation unit. This produced a 100-millisecond train of 10 square-wave pulses at an intensity of 125 V (pulse duration = 600 microseconds, frequency = 100 Hz).¹⁸ The SIB stimulus was administered when the investigator saw a plateau in the real-time torque display. One minute of rest was given between trials. The last 3 trials of maximal contractions were used as F_{MVIC} and F_{SIB} .

Data Analysis

Hip-abduction F_{MVIC} data were converted to torque (newton meters) and normalized to body mass (newton meters per kilogram). Hip-abduction F_{MVIC} was calculated with the average

torque produced over a 100-millisecond epoch before the stimulus, averaged over the 3 trials. The calculation for the CAR used this same average torque before the SIB and the maximal torque output that occurs with the stimulus (F_{SIB}), multiplied by 100, represented by the equation below¹⁸:

$$CAR = \frac{F_{MVIC}}{(F_{MVIC} + F_{SIB})} \times 100$$

The CAR is displayed as a percentage, between 0% and 100%, and represents the level of muscular activation; 100% indicates full activation of the muscle is achieved voluntarily.

Statistical Analysis

A general linear model was used to determine if there was a significant difference in the average gluteus medius CAR between groups while controlling for age, mass, and average hip-abduction MVIC. The variables of age, mass, and average hip-abduction MVIC were included to (1) make sure that each variable was not a confounder of group (eg, group differences may be explained by mass rather than the effect of group) and (2) identify the independent effect of group when controlling for possible effects of age, mass, and gluteus medius MVIC on the CAR. This is particularly relevant because hip abduction directly influences the CAR, as it is part of the equation. Body mass has been shown to be associated with PFP,²² and age has been shown to influence hip strength.²³

Table 2. Participant Characteristics

Characteristic	Mean $\pm$ SD		<i>P</i> Value ^a
	Pain-free (n = 13)	PFP (n = 15)	
Age, y	21.6 $\pm$ 3.6	22.3 $\pm$ 3.2	0.5
Mass, kg	65.4 $\pm$ 11.3	75.3 $\pm$ 22.6	0.2
Height, m	1.66 $\pm$ 0.06	1.66 $\pm$ 0.07	>0.9
Pain duration, mo	N/A	41.4 $\pm$ 27.9	N/A
Gluteus medius MVIC	1.15 $\pm$ 0.16	1.36 $\pm$ 0.44	0.3
Gluteus medius CAR	0.98 $\pm$ 0.01	0.94 $\pm$ 0.06	0.004

Abbreviations: CAR, central activation ratio; MVIC, maximal voluntary isometric contraction; PFP, patellofemoral pain.

^a Wilcoxon rank sum test.

The raw values of the gluteus medius CAR presented a high left skewness due to several participants having a gluteus medius CAR near 100%. To meet the assumption of normality, we transformed the gluteus medius CAR by raising it to the 20th power (CAR²⁰; Shapiro-Wilk test *P* = .07, *W* = 0.93).²⁴ If there was a significant difference of group, we back transformed the data of the mean difference between groups by raising it to the power 1/20 so that inferences could be made based on the original gluteus medius CAR unit scale.²⁴ To control for multicollinearity between independent variables, we scaled variables of age, mass, and hip-abduction MVIC and confirmed low collinearity by calculating the variance inflation factor for each variable. Presence of outliers was determined based on the calculated Cook

distance of each data point with a threshold of less than 0.5. Significance was accepted when *P* < .05 (R version 4.4.1). After transformation of the CAR (CAR²⁰), no outliers needed to be removed.

RESULTS

The participant demographics and characteristics are presented in Table 2. The results of the general linear model demonstrated a statistically significant main effect of group ($F_{1,26} = 10.4$, *P* = .004). Women with PFP had a lower gluteus medius CAR than women without PFP even after accounting for age (*P* = .29), mass (*P* = .24), and hip-abduction MVIC (*P* = .29). We confirmed that results of the analysis possessed no outliers, and collinearity between predictor variables was in the appropriate range. The estimated differences between groups were -0.28 gluteus medius CAR (95% CI = -0.45 , -0.1 ; average control gluteus medius CAR = 0.72; average gluteus medius CAR PFP = 0.44). Back transformation of the estimated mean group difference equated to 2.5% gluteus medius CAR (average control gluteus medius CAR = 98.4%, PFP = 95.9%, estimated effect size = 1.35; 95% CI = 0.39, 2.3; large effect). Overall, after controlling for participant age, mass, and hip-abduction MVIC, the PFP group had an average gluteus medius CAR score 2.5% lower than that of the pain-free control group. Figure 2 shows the results found for the gluteus medius CAR and gluteus medius MVIC.

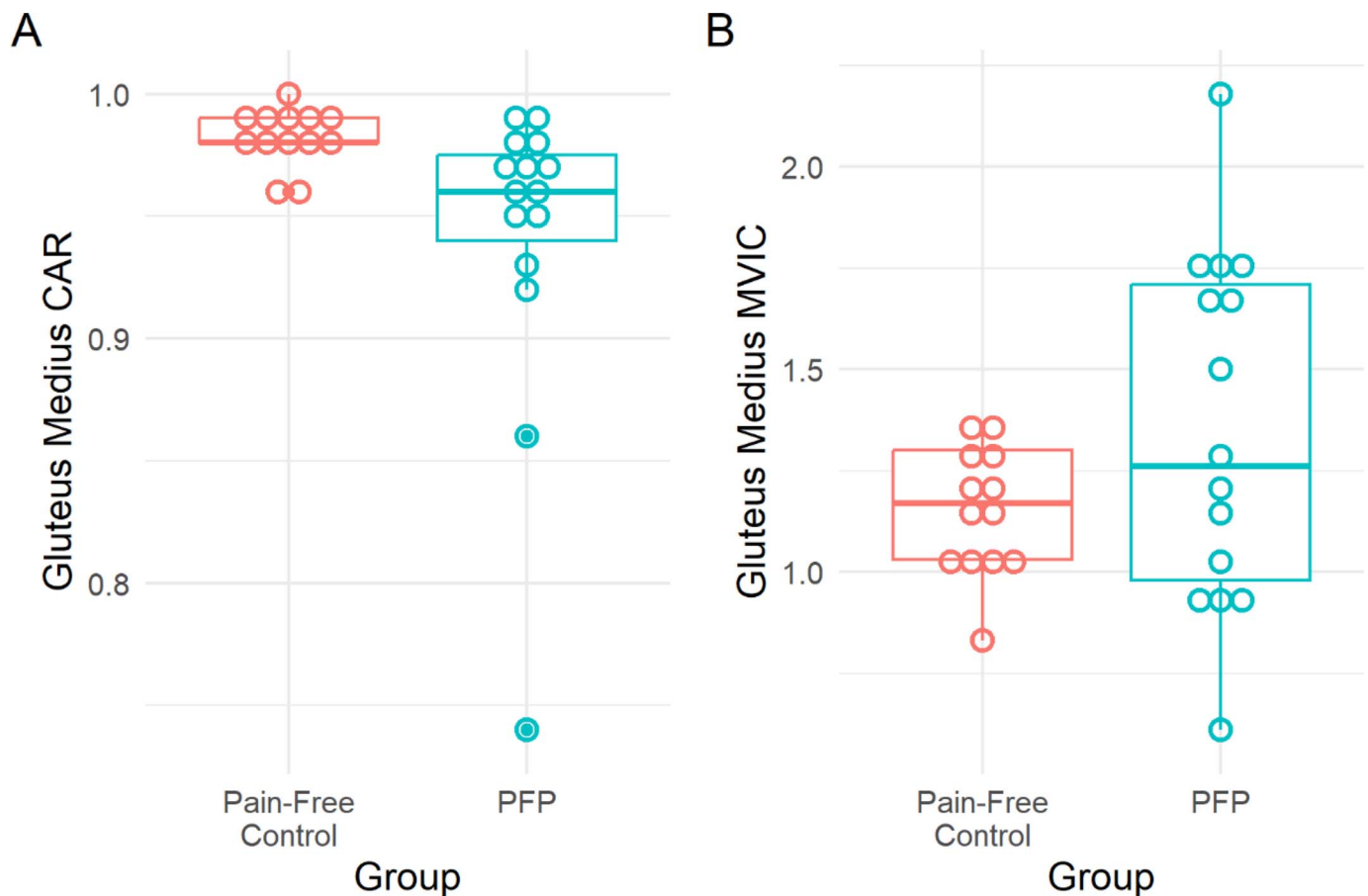


Figure 2. A, Gluteus medius central activation ratio (CAR; %), and B, gluteus medius strength (maximal voluntary isometric contraction [MVIC]; N-m/kg), compared with controls. Abbreviation: PFP indicates patellofemoral pain.

DISCUSSION

The purpose of this study was to determine if individuals with PFP have a lower CAR for the gluteus medius when compared with pain-free controls. The main observation of this study indicated that women with PFP have a significantly lower CAR than pain-free controls. It is important to note that, although a difference was found, the gluteus medius activation levels ranged from 74% to 99% within the PFP group. This is not surprising, because PFP is multifactorial, with numerous underlying factors associated with the development and progression of the condition, resulting in a patient population that presents with a diverse range of symptoms and functional abnormalities. Both findings, including the reduced CAR and varied activation levels, agree with the first study conducted that examined whether females with PFP exhibited lower gluteal muscle activation.¹⁹ This study used the same methodology for the CAR assessment of the gluteus medius with a smaller cohort of females with PFP.¹⁹

The average gluteus medius CAR for women with PFP was 95.9%, whereas the average for pain-free controls was 98.4%. Our findings for gluteus medius activation were slightly higher for both groups compared with prior research, wherein the CAR was between 96.1% and 96.6% for healthy women¹⁸ and 90.5% for women with PFP.¹⁹ These previous studies differed in that one had a smaller cohort of female participants with PFP ($n = 7$) and did not include a healthy cohort for direct comparison,¹⁹ and the other assessed only a healthy cohort ($n = 20$) with both males and females to establish validity and reliability of the CAR for the gluteal muscles.¹⁸

One interesting finding was that the PFP group in our study had similar hip-abduction torque (1.36 N·m/kg) when compared with the control group (1.15 N·m/kg). This could indicate that, although the PFP group had similar hip-abduction strength, due to decreased activation of the gluteus medius, they may have relied on other muscles to compensate and generate the abduction torque (ie, tensor fasciae latae, gluteus maximus). The gluteus medius is an important stabilizer muscle functioning to maintain neutral alignment of the lower extremity in the frontal plane during dynamic movement.⁶ During functional activities, such as running, the demand on the gluteus medius was found to peak at an activation at 112.4% of MVIC and to average 81.4% of MVIC in a group of women with PFP, which was not significantly different from the comparison healthy control group.²⁵ However, female participants with PFP did display gluteus medius activation that was delayed and shorter in duration during running.²⁵ This provides another example to illustrate the importance of using specific assessment tools to examine different aspects of neuromuscular control.²⁵

Although a standard of care exists for the treatment and rehabilitation of PFP, the long-term outcomes are poor, resulting in abnormal findings such as persistent pain,^{26–28} restrictions in both daily^{26,27} and physical^{26–28} activities, and no improvements in hip^{29,30} and quadriceps³¹ strength. A recent theoretical model suggests some of these abnormal findings, specifically a lack of improved strength, could be related to an underlying influence of muscle inhibition, which provided the motivation for the current study.¹⁵ The findings from our study could provide some insight to explain why some individuals with PFP may be unresponsive to strengthening of the gluteus medius. For example, our study had 4 participants with a CAR less than 95%, suggesting altered gluteus medius muscle function for these individuals. This also indicates that not all individuals

with PFP exhibit impaired gluteus medius voluntary activation, but some do. This heterogeneous symptomology provides justification to consider adjusting our current practice for evaluation and treatment of PFP for individuals identified with reduced voluntary activation.

One way to address heterogeneous symptomology could be subgrouping patients by their prominent impairment, such as impaired voluntary activation, and then designing their treatment with interventions focused on the prominent impairment. Subgrouping of individuals with PFP has been suggested and studied with success and improved outcomes.^{32,33} The wide range in gluteus medius activation found in our study (74% to 99%) would support the concept of subgrouping.

Subgrouping was recommended after it was determined that one-third of patients in a randomized controlled clinical trial were unresponsive to a strengthening protocol,³⁰ and 3 subgroups³³ were first suggested after 127 patients were evaluated for similarities. Current clinical practice for PFP does not involve specific approaches to address inhibition, which could mean clinicians are not able to provide optimal treatment. In addition, there currently is not a clinician-friendly approach to determine if a patient has muscle inhibition because very specific equipment is necessary to assess the CAR. Therefore, it could be suggested that a subgroup should be created for patients who are unresponsive to strengthening protocols to attempt to determine if this is related to impaired voluntary activation. Future researchers could evaluate nonresponders to determine if muscle inhibition may explain their lack of success with a traditional strengthening protocol. Establishing muscle inhibition's connection to nonresponders could lead to research that could determine effective treatment strategies for individuals with PFP who demonstrate inhibition of the gluteus medius. Disinhibitory modalities, such as focal joint cooling or conventional transcutaneous electrical nerve stimulation to the knee joint, have been used for treating inhibition; however, clinicians should be aware these interventions have only been evaluated for quadriceps inhibition and not for gluteal inhibition.³⁴ Before tailored rehabilitation for individuals with gluteal inhibition can be recommended, future researchers should compare potential interventions that have been successful at addressing inhibition of other muscles.

Clinical Implications

Assessment tools to detect specific muscle function deficiency are important for interventions aimed to improve long-term outcomes associated with PFP. Although some patients seek care for PFP, patients who undergo standard care continue to have ongoing difficulties from 4^{26,27} to 8 years²⁸ after diagnosis, including persistent pain^{26–28} and restrictions in both daily^{26,27} and physical activities.^{26,28} In addition, some patients with PFP are not responsive to traditional strengthening treatments.^{29–31} The results of this study indicated that a wide range of gluteus medius activation exists among women with PFP. For this reason, identifying the presence of impaired voluntary activation may be useful for clinicians to determine the most appropriate treatment techniques.

Limitations

One potential limitation for this study may be the testing position used for assessing hip abduction. We performed

hip abduction with the participant standing as opposed to side lying. Although side lying would provide greater comfort to the participant, we found during pilot testing that participants were not able to exert maximal contractions, likely because of gravity and instability, during side lying. Because the SIB technique requires maximal contraction, the standing position was preferred and used. Moreover, the standing position is the only reliable and valid method to assess the gluteus medius CAR.¹⁸ Second, participants with bilateral PFP performed testing on the most symptomatic side. Consequently, the contralateral side still provided sufficient stabilizing force as the stance leg, and this demand could affect the performance of those with bilateral PFP. Third, we assessed voluntary activation of only the gluteus medius in this study. We focused on the gluteus medius because deficits in strength and activation are common deficits found in individuals with PFP.^{6–10} However, differences in voluntary activation may exist because additional muscles also contribute to hip abduction. Fourth, this study involved women only, which limits the generalizability of our findings. Lastly, current PFP pain was not an outcome measure for this study. It is possible that experiencing pain while completing CAR testing could influence the participant's ability to fully activate the gluteus medius. Future CAR researchers should include a pain measure to determine how the presence of pain may influence voluntary activation of the gluteus medius.

CONCLUSIONS

Women with PFP had reduced voluntary activation of the gluteus medius and presented with a wide range of gluteus medius activation levels. Moreover, inhibition was not present in all women with PFP, indicating further that assessment of gluteus medius voluntary activation should occur in patients with PFP to determine the most effective treatment strategies.

FINANCIAL DISCLOSURE

Dr Lee reports grants from the Department of Defense, grants from the National Institutes of Health, and personal fees from the Symposium on Advanced Wound Care outside the submitted work; in addition, Dr Lee has a patent to Method and Apparatus for Performing Timed Up-And-Go Test issued.

REFERENCES

- Glaviano NR, Kew M, Hart JM, Saliba S. Demographic and epidemiological trends in patellofemoral pain. *Int J Sports Phys Ther*. 2015;10(3):281–290.
- Devereaux MD, Lachmann SM. Patello-femoral arthralgia in athletes attending a sports injury clinic. *Br J Sports Med*. 1984;18(1):18–21. doi:10.1136/bjism.18.1.18
- Crossley KM, van Middelkoop M, Callaghan MJ, Collins NJ, Rathleff MS, Barton CJ. 2016 Patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester, part II: recommended physical interventions (exercise, taping, bracing, foot orthoses and combined interventions). *Br J Sports Med*. 2016;50(14):844–852. doi:10.1136/bjsports-2016-096268
- Powers CM, Witvrouw E, Davis IS, Crossley KM. Evidence-based framework for a pathomechanical model of patellofemoral pain: 2017 patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester, UK, part III. *Br J Sports Med*. 2017;51(24):1713–1723. doi:10.1136/bjsports-2017-098717
- Neal BS, Lack SD, Lankhorst NE, Raye A, Morrissey D, van Middelkoop M. Risk factors for patellofemoral pain: a systematic review and meta-analysis. *Br J Sports Med*. 2019;53(5):270–281. doi:10.1136/bjsports-2017-098890
- Powers CM. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *J Orthop Sports Phys Ther*. 2010;40(2):42–51. doi:10.2519/jospt.2010.3337
- Lankhorst NE, Bierma-Zeinstra SM, van Middelkoop M. Factors associated with patellofemoral pain syndrome: a systematic review. *Br J Sports Med*. 2013;47(4):193–206. doi:10.1136/bjsports-2011-090369
- Prins MR, van der Wurff P. Females with patellofemoral pain syndrome have weak hip muscles: a systematic review. *Aust J Physiother*. 2009;55(1):9–15. doi:10.1016/S0004-9514(09)70055-8
- Powers CM, Bolgia LA, Callaghan MJ, Collins N, Sheehan FT. Patellofemoral pain: proximal, distal, and local factors—second International Research Retreat, August 31–September 2, 2011, Ghent, Belgium. *J Orthop Sports Phys Ther*. 2012;42(6):A1–A54. doi:10.2519/jospt.2012.0301
- Souza RB, Powers CM. Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. *J Orthop Sports Phys Ther*. 2009;39(1):12–19. doi:10.2519/jospt.2009.2885
- Barton CJ, Lack S, Malliaras P, Morrissey D. Gluteal muscle activity and patellofemoral pain syndrome: a systematic review. *Br J Sports Med*. 2013;47(4):207–214. doi:10.1136/bjsports-2012-090953
- Boling MC, Bolgia LA, Mattacola CG, Uhl TL, Hosey RG. Outcomes of a weight-bearing rehabilitation program for patients diagnosed with patellofemoral pain syndrome. *Arch Phys Med Rehabil*. 2006;87(11):1428–1435. doi:10.1016/j.apmr.2006.07.264
- Ferber R, Kendall KD, Farr L. Changes in knee biomechanics after a hip-abductor strengthening protocol for runners with patellofemoral pain syndrome. *J Athl Train*. 2011;46(2):142–149. doi:10.4085/1062-6050-46.2.142
- Willy RW, Davis IS. The effect of a hip-strengthening program on mechanics during running and during a single-leg squat. *J Orthop Sports Phys Ther*. 2011;41(9):625–632. doi:10.2519/jospt.2011.3470
- Glaviano NR, Bazett-Jones DM, Norte G. Gluteal muscle inhibition: consequences of patellofemoral pain? *Med Hypotheses*. 2019;126:9–14. doi:10.1016/j.mehy.2019.02.046
- Hart JM, Pietrosimone B, Hertel J, Ingersoll CD. Quadriceps activation following knee injuries: a systematic review. *J Athl Train*. 2010;45(1):87–97. doi:10.4085/1062-6050-45.1.87
- Norte GE, Frye JL, Hart JM. Reliability of the superimposed-burst technique in patients with patellofemoral pain: a technical report. *J Athl Train*. 2015;50(11):1207–1211. doi:10.4085/1062-6050-50.10.03
- Gilfeather D, Norte G, Ingersoll CD, Glaviano NR. Central activation ratio is a reliable measure for gluteal neuromuscular function. *J Sport Rehabil*. 2019;29(7):956–962. doi:10.1123/jsr.2019-0243
- Glaviano NR, Norte GE. Gluteal central activation in females with patellofemoral pain: a preliminary study. *J Sport Rehabil*. 2021;31(6):676–683. doi:10.1123/jsr.2021-0093
- von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP; STROBE Initiative. The Strengthening of Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *PLoS Med*. 2007;4(10):e296. doi:10.1371/journal.pmed.0040296
- Barton CJ, De Oliveira Silva D, Morton S, et al. REPORT-PFP: a consensus from the International Patellofemoral Research Network to improve REPORTing of quantitative Patellofemoral Pain studies. *Br J Sports Med*. 2021;55(20):1135–1143. doi:10.1136/bjsports-2020-103700
- Hart HF, Barton CJ, Khan KM, Riel H, Crossley KM. Is body mass index associated with patellofemoral pain and patellofemoral osteoarthritis? A systematic review and meta-regression and analysis. *Br J Sports Med*. 2017;51(10):781–790. doi:10.1136/bjsports-2016-096768
- Dean JC, Kuo AD, Alexander NB. Age-related changes in maximal hip strength and movement speed. *J Gerontol A Biol Sci Med Sci*. 2004;59(3):286–292. doi:10.1093/gerona/59.3.m286
- Lee DK. Data transformation: a focus on the interpretation. *Korean J Anesthesiol*. 2020;73(6):503–508. doi:10.4097/kja.20137

25. Willson JD, Kernozek TW, Arndt RL, Reznicek DA, Scott Straker J. Gluteal muscle activation during running in females with and without patellofemoral pain syndrome. *Clin Biomech (Bristol)*. 2011;26(7):735–740. doi:10.1016/j.clinbiomech.2011.02.012
26. Stathopulu E, Baildam E. Anterior knee pain: a long-term follow-up. *Rheumatology (Oxford)*. 2003;42(2):380–382. doi:10.1093/rheumatology/keg093
27. Price AJ, Jones J, Allum R. Chronic traumatic anterior knee pain. *Injury*. 2000;31(5):373–378. doi:10.1016/S0020-1383(00)00006-1
28. Sandow MJ, Goodfellow JW. The natural history of anterior knee pain in adolescents. *J Bone Joint Surg Br*. 1985;67(1):36–38. doi:10.1302/0301-620X.67B1.3968140
29. Nakagawa TH, Muniz TB, de Marche Baldon R, Dias Maciel C, de Menezes Reiff RB, Serrão FV. The effect of additional strengthening of hip abductor and lateral rotator muscles in patellofemoral pain syndrome: a randomized controlled pilot study. *Clin Rehabil*. 2008;22(12):1051–1060. doi:10.1177/0269215508095357
30. Bolgla LA, Earl-Boehm J, Emery C, Hamstra-Wright K, Ferber R. Pain, function, and strength outcomes for males and females with patellofemoral pain who participate in either a hip/core- or knee-based rehabilitation program. *Int J Sports Phys Ther*. 2016;11(6):926–935.
31. Dolak KL, Silkman C, Medina McKeon J, Hosey RG, Lattermann C, Uhl TL. Hip strengthening prior to functional exercises reduces pain sooner than quadriceps strengthening in females with patellofemoral pain syndrome: a randomized clinical trial. *J Orthop Sports Phys Ther*. 2011;41(8):560–570. doi:10.2519/jospt.2011.3499
32. Keays SL, Mason M, Newcombe PA. Individualized physiotherapy in the treatment of patellofemoral pain. *Physiother Res Int*. 2015;20(1):22–36. doi:10.1002/pri.1593
33. Selfe J, Janssen J, Callaghan M, et al. Are there three main subgroups within the patellofemoral pain population? A detailed characterisation study of 127 patients to help develop targeted intervention (TIPPs). *Br J Sports Med*. 2016;50(14):873–880. doi:10.1136/bjsports-2015-094792
34. Norte G, Rush J, Sherman D. Arthrogenic muscle inhibition: best evidence, mechanisms, and theory for treating the unseen in clinical rehabilitation. *J Sport Rehabil*. 2022;31(6):717–735. doi:10.1123/jsr.2021-0139

Address correspondence to Michelle N. Samuel, PhD, ATC, Department of Kinesiology and Nutrition Sciences, University of Nevada, Las Vegas, 4505 S Maryland Parkway, Las Vegas, NV 89154-3034. Address email to michelle.samuel@unlv.edu.