European Journal of Applied Physiology
https://doi.org/10.1007/s00421-026-06381-9

ORIGINAL ARTICLE

# Fatigue-induced changes in VMO–VL EMG correlation in individuals with patellofemoral pain

**Zhong Wang**[1] · **Lisa Griffin**[2]

Received: 19 March 2026 / Accepted: 22 July 2026


**Abstract**

**Purpose** Patellofemoral pain (PFP) is commonly aggravated during prolonged activity, suggesting that neuromuscular responses to fatigue may influence quadriceps activation. We examined how fatigue affects the similarity of activation between the vastus medialis oblique (VMO) and vastus lateralis (VL) in individuals with and without PFP, and whether responses differ by sex.

**Methods** Twenty-three patients with PFP (11 females, 12 males) and 23 non-injured controls (13 females, 10 males) performed sustained isometric knee extensions at 20% maximal voluntary contraction until task failure. VMO–VL activation similarity was quantified using cross-correlation of surface and intramuscular EMG amplitude envelopes across four equal phases of fatigue. Peak correlation reflected maximal temporal similarity of activation, and integrated correlation strength (ICS) represented overall correlation magnitude.

**Results** Peak correlation and ICS increased progressively with fatigue in all groups ($p < 0.001$). However, fatigue-related increases were significantly smaller in individuals with PFP and in females compared with non-injured males. Pre-fatigue values did not differ between groups. Surface and intramuscular EMG showed comparable fatigue-related trends.

**Conclusion** Fatigue increased VMO–VL EMG cross-correlation in healthy participants, whereas this fatigue-related increase was attenuated in individuals with PFP. These findings suggest reduced capacity to adapt quadriceps activation patterns during sustained load in PFP, supporting fatigue as a useful physiological stressor for evaluating quadriceps function.

**Keywords** Electromyography · Knee · Vastus medialis · Vastus lateralis

## Introduction

Neuromuscular fatigue is characterized by a progressive reduction in force-generating capacity arising from central and peripheral mechanisms, including altered motor output and impaired contractile function (Enoka and Stuart 1992). During sustained isometric contractions, maintaining target force requires adjustments in activation patterns across synergistic muscles. In healthy individuals, fatigue has been associated with increased similarity of activation between synergists, reflected by greater correlation of EMG amplitude patterns (Rainoldi et al. 2008; Stock et al. 2012; Castronovo et al. 2015). These findings suggest that fatigue may alter the relationship between synergistic muscles as task demands increase.

The vastus medialis oblique (VMO) and vastus lateralis (VL) act as synergists in knee extension and contribute to mediolateral force regulation at the patellofemoral joint. In healthy populations, coordinated activation of the VMO and VL has been demonstrated using both time- and frequency-domain EMG analyses (Chang et al. 2012; Laine et al. 2015). Altered timing or synchronization between these muscles has been reported in individuals with patellofemoral pain (PFP), suggesting potential deficits in quadriceps control (Cowan et al. 2001; Mellor and Hodges 2005; Cavazzuti et al. 2010). However, most studies have examined VMO–VL activation patterns under non-fatigued conditions.

Communicated by Andrew Cresswell.

✉ Lisa Griffin
l.griffin@austin.utexas.edu

1 Department of Kinesiology and Educational Psychology, College of Education, Sport and Human Sciences, Washington State University, Pullman, WA 99164, USA

2 Department of Kinesiology and Health Education, The University of Texas at Austin, Austin, TX 78712, USA

Published online: 06 August 2026

Fatigue is commonly experienced during daily and athletic activities and has been associated with symptom provocation in PFP (Van Tiggelen et al. 2009; Crossley et al. 2016). In healthy individuals, VMO–VL cross-correlation increases during fatigue (Chang et al. 2012; Boonstra et al. 2016), potentially reflecting adaptive changes in synergistic activation as force production declines. Whether individuals with PFP demonstrate similar fatigue-related adjustments in VMO–VL EMG correlation remains unclear. In this context, fatigue may serve as a physiological stressor that reveals deficits not evident under unfatigued conditions. Given the higher prevalence of PFP in females and reported sex differences in fatigability (Hunter 2016), potential sex-related differences in fatigue-related responses also warrant examination.

Because cross-correlation derived from surface EMG can be influenced by volume conduction between adjacent muscles, intramuscular EMG was included to provide a localized recording with minimal intermuscular interference and to confirm that fatigue-related changes in VMO–VL correlation were not dependent on surface recordings alone.

The purpose of this study was to examine EMG correlation between the VMO and VL during a sustained isometric fatiguing contraction in individuals with and without PFP, quantified using time-domain cross-correlation of EMG amplitude envelopes. We hypothesized that VMO–VL cross-correlation would increase with fatigue in healthy individuals, but that this fatigue-related increase would be attenuated in participants with PFP and in females.

## Methods

### Participants

Twenty-three participants with PFP (11 females and 12 males, aged 23.9 ± 6.5 years) and 23 non-injured individuals (13 females and 10 males, aged 22.5 ± 3.2 years) participated. All participants were physically active and reported no history of lower extremity surgery, neurological disorders, or other knee pathology.

Participants with PFP met the following inclusion criteria: (1) anterior knee pain rated ≥ 3 out of 10 on a visual analog scale at rest or aggravated by at least two common PFP-provoking activities (stair ascent or descent, squatting, kneeling, prolonged sitting, jogging/running, hopping, or jumping); (2) pain duration > 2 months; (3) no history of traumatic injury, knee dislocation, or surgery to the lower limb; and (4) no known cardiovascular or neurological disorders. All participants with PFP had previously received a clinical diagnosis of patellofemoral pain at rehabilitation clinics. Diagnosis was reconfirmed via a screening interview and the Kujala Anterior Knee Pain Scale (score ≤ 85) (Kujala et al. 1993), consistent with established consensus criteria (Crossley et al. 2016).

Control participants had no history of knee or lower-limb injury, neurological or cardiovascular conditions, metal implants, pacemakers, or prior lower-limb surgery.

All participants provided written informed consent prior to testing. The study protocol was approved by the Institutional Review Board at The University of Texas at Austin.

### Experimental procedures

Testing was performed on the dominant leg while participants were seated in a custom-built chair with the torso and hips stabilized by straps and the feet unsupported. For participants with unilateral or bilateral PFP, the more symptomatic limb was tested. For control participants, leg dominance was determined as the preferred leg used to kick a ball. The knee was flexed to 90°, and the ankle was secured to a compression–tension load cell (LC203-100, OMEGA, USA) connected to a bridge amplifier (DMD4059, OMEGA). The system was shunt-calibrated before each session to ensure accuracy.

Participants performed three maximal voluntary contractions (MVCs) of isometric knee extension, each held for 3 s with 30 s rest. The highest plateau was recorded as the prefatigue MVC. After a 5 min rest, participants maintained a constant force at 20% MVC until failure, defined as force deviation > ± 5% MVC or a drop below 15% MVC. Real-time visual feedback of target and produced force was displayed on a monitor. Three MVCs were repeated immediately post-fatigue using the same protocol.

### Electrode placement and EMG acquisition

Surface and intramuscular EMG were collected to evaluate VMO–VL cross-correlation at both whole-muscle and localized motor-unit levels while providing complementary evidence regarding potential crosstalk effects. The illustration of VMO–VL intermuscular correlation and patellar control and EMG electrode placement are shown in Figure 1. Surface EMG (sEMG) was recorded using Ag/AgCl bipolar electrodes (0.75 × 1.125 in., Danlee Medical, NY) placed according to SENIAM guidelines and previous studies (Tenan et al. 2016; Peng et al. 2018). Electrodes for the vastus medialis oblique (VMO) were positioned superomedial and proximal to the patella at an orientation of 55° to the femoral axis; electrodes for the vastus lateralis (VL) were positioned superolateral to the patella at 15°. Each bipolar pair had a 25 mm center-to-center spacing, placed midway between the muscle's innervation zone and border. The intermuscular distance between VMO and VL electrode

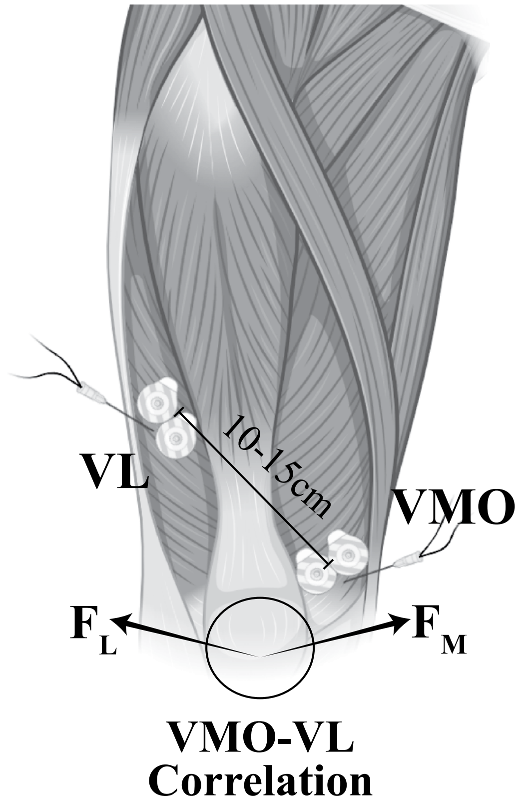


**Fig. 1** Experimental overview and electrode placement. Surface and fine-wire intramuscular EMG electrodes placed over the vastus medialis oblique (VMO) and vastus lateralis (VL), with 10–15 cm intermuscular distance between recording sites

centers was 10–15 cm, representing less than one-third of each muscle's width and minimizing crosstalk risk (Winter et al. 1994; Vieira and Botter 2021). The skin was cleaned with 70% isopropyl alcohol and shaved if necessary.

Fine-wire intramuscular EMG (iEMG) electrodes were inserted adjacent to the sEMG electrodes (~0.5–1 cm depth) using sterilized hypodermic needles to provide localized recordings with minimal intermuscular interference (Muceli et al. 2015). The reference electrode was placed on the ipsilateral patella.

Signals were amplified (gain = 1,000×), digitized at 16-bit resolution (±5 mV range), and recorded at 2 kHz (sEMG) and 10 kHz (iEMG). Force signals were acquired at 1 kHz using a Micro 1401 A/D converter (Cambridge Electronic Design, UK). Force and EMG data were analyzed in Spike 2 (v10.16, CED) and custom Python scripts. sEMG signals were band-pass filtered 15–500 Hz and iEMG 100 Hz–8 kHz (4th-order Butterworth) with a 60 Hz notch filter. Filtering parameters were selected to minimize motion artifact while preserving physiological signal content (De Luca 1997; Farina et al. 2013).

Root mean square (RMS) amplitude envelopes were computed from both sEMG AND iEMG signals using a 10 ms moving window, corresponding to an effective low-pass cutoff of ~100 Hz—appropriate for analyzing motor-unit synchronization bandwidths (Boonstra et al. 2008). EMG amplitudes were expressed as % MVC relative to the prefatigue RMS. All EMG acquisition and analysis procedures conformed to the standards for reporting EMG data.

### Quantifying VMO–VL cross-correlation

VMO and VL correlation was quantified separately for sEMG and iEMG using time-domain cross-correlation (XCOR) of their RMS EMG signals (Figure 2). Endurance time was divided into four equal phases to examine the temporal evolution of cross-correlation across progressive fatigue.

Signal was demeaned prior to correlation to remove DC bias. A 100 ms correlation window (±50 ms lag) was applied, reflecting previously reported maximal delays between VMO and VL activation (Chester et al. 2008).

From each cross-correlation curve, two indices were extracted across fatigue:

1. Peak correlation coefficient: maximum correlation magnitude within the lag window, reflecting temporal similarity of activation.
2. Integrated Correlation Strength (ICS): area under the positive portion of the cross-correlation curve, reflecting overall magnitude of correlated activation.

Cross-correlation of EMG amplitude envelopes reflects temporal similarity in muscle activation patterns and is interpreted here as an intermuscular correlation metric rather than a direct measure of shared neural input.

Both indices were calculated for sEMG and iEMG. The lag of maximum correlation was recorded to assess relative timing differences; no systematic phase shift was observed. Fatigue-induced changes were calculated as Phase 4 – Phase 1 and normalized to Phase 1.

### Crosstalk control

Crosstalk was addressed through (1) wide intermuscular electrode separation (10–15 cm), (2) comparison of cross-correlation results obtained independently from sEMG and iEMG recordings, and (3) zero-lag correlation of raw EMG signals, all yielding coefficients < 0.1. While correlation of raw signals does not fully quantify volume conduction (Lowery et al. 2003), this combination of anatomical, signal, and modality controls indicated minimal crosstalk influence. EMG crosstalk from adjacent muscles is minimized to 1%–2% at interelectrode distances of 7.5 cm(Winter et al. 1994).

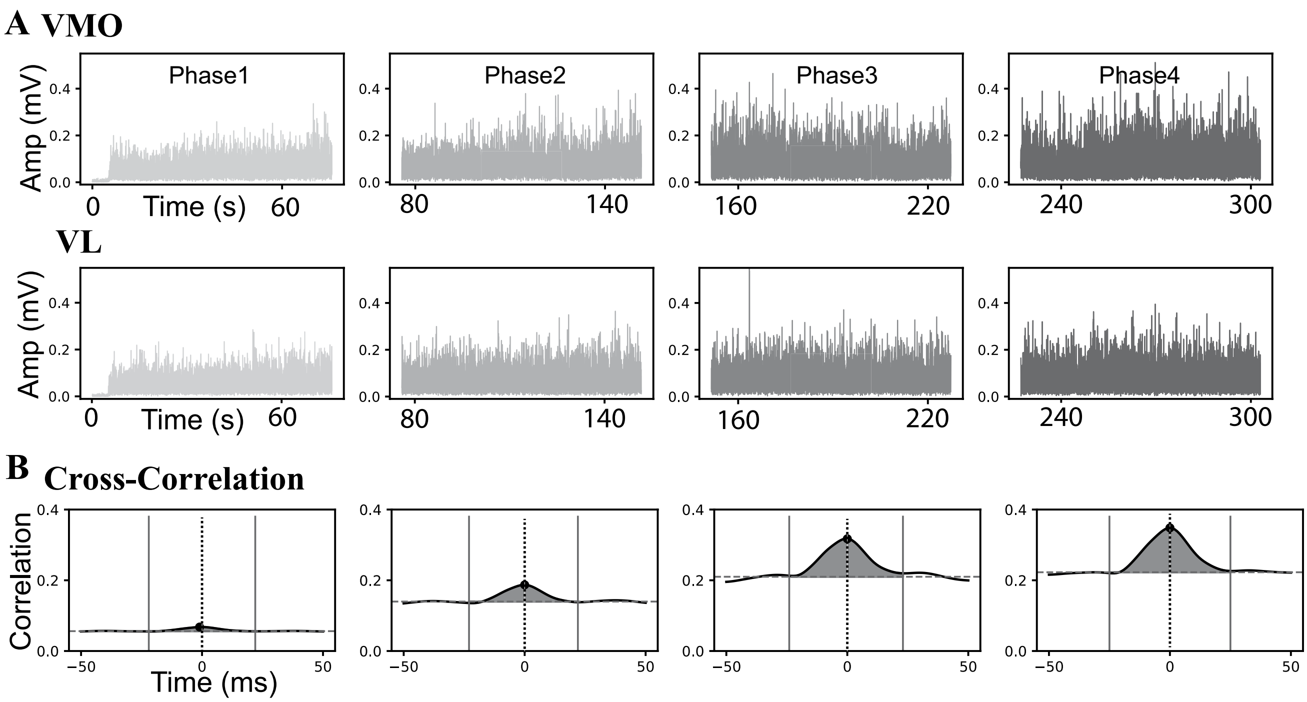


**Fig. 2** Quantification of VMO–VL sEMG cross-correlation during fatigue. **A** Representative RMS surface EMG signals from the VMO and VL across four equal phases of a sustained 20% maximal voluntary contraction. **B** Cross-correlation of VMO and VL RMS surface EMG signals for each fatigue phase. The peak correlation coefficient represents maximal temporal similarity within ± 50 ms lag. The shaded area indicates integrated correlation strength (ICS), reflecting overall magnitude of correlated activation

## Statistical analyses

Statistical analyses were conducted using Pingouin(Vallat 2018) and JASP (Version 0.95). To compare group differences in prefatigue MVC torque, task intensity, and endurance time, a two-way ANOVA was used for comparisons across sex and PFP status non-injured males, non-injured females, females with PFP, and males with PFP). To examine the gradual changes across fatigue phases, a three-way repeated-measures ANOVA (PFP status, sex, and fatigue phases) was used to examine differences in normalized EMG amplitude (% MVC EMG), XCOR peaks, ICS values, and fatigue-induced increases (relative to baseline) in both sEMG and iEMG.

Violation of sphericity was corrected using Greenhouse–Geisser adjustment. For post-hoc analyses, Tukey HSD tests with multiple comparison corrections were used for pairwise comparisons. A significance level of $\alpha = 0.05$ was used for all analyses, and all data are reported and displayed as means ± standard errors.

## Results

### Task fatigability

Supplementary Table 1 summarizes prefatigue knee-extension torque, effective task intensity, and endurance time. Knee-extension MVC (Nm) showed a significant main effect of sex ($p < 0.001$), with no main effect of PFP status and no sex × PFP interaction. MVC torque was lower in females with PFP (PFP-F) compared with non-injured males (NI-M; $p = 0.007$). Non-injured females (NI-F) also produced lower torque than NI-M ($p < 0.001$) and males with PFP (PFP-M; $p = 0.035$). There were no significant main effects of sex or PFP status, and no interaction effects, for either task intensity or endurance time.

### EMG amplitudes during fatigue

Supplementary Figure S1 illustrates VMO and VL EMG amplitudes (%MVC) across fatigue phases. There was a significant main effect of fatigue for both muscles ($p < 0.001$). VMO amplitude increased progressively across phases (Phase 2–4 relative to Phase 1: + 2.2 ± 0.3%, + 3.7 ± 0.4%, + 5.9 ± 0.6%; all $p < 0.001$). VL amplitude showed similar increases (+ 2.5 ± 0.2%, + 4.1 ± 0.4%, + 6.1 ± 0.6%; all

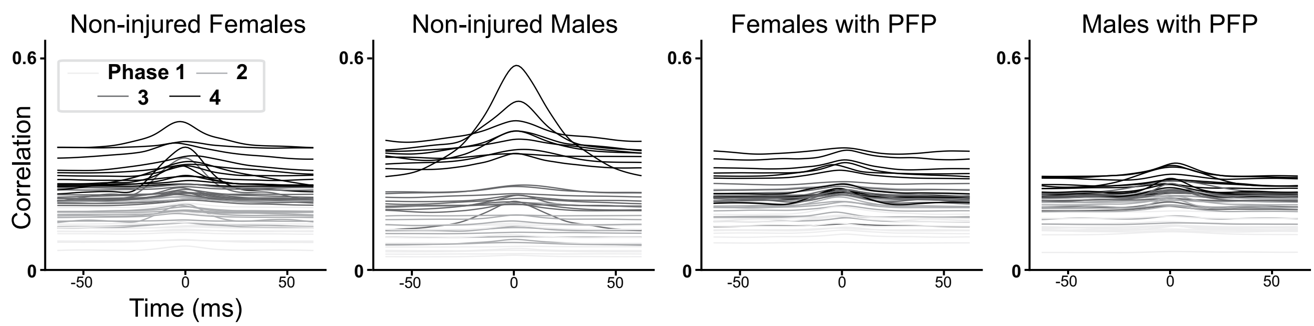


**Fig. 3** VMO–VL surface EMG cross-correlation patterns during fatigue. Representative sEMG-derived cross-correlation curves across four fatigue phases for each group. Line shading from light to dark indicates Phases 1-4. Non-injured groups exhibited progressive increases in correlation magnitude, whereas participants with patellofemoral pain (PFP) showed smaller increases

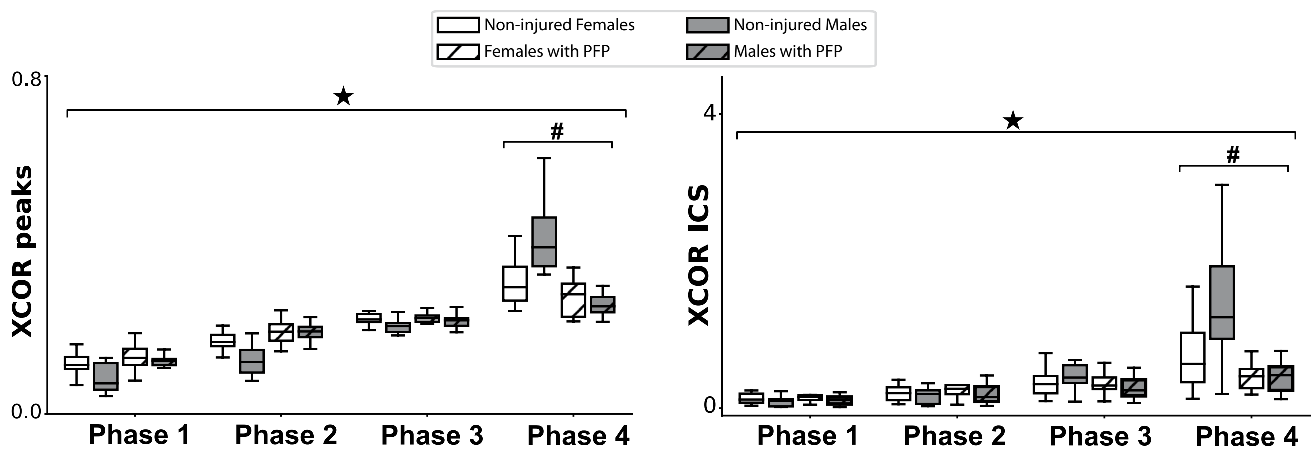


**Fig. 4** Group differences in VMO–VL surface EMG cross-correlation across fatigue phases. Box-and-whisker plots of sEMG-derived peak cross-correlation (left) and integrated correlation strength (ICS) (right) across four fatigue phases. Both indices increased with fatigue (★ main effect, P<0.001). In Phase 4, individuals with PFP and females exhibited lower correlation values compared with non-injured males (* P<0.05)

p<0.001). No significant effects of sex or PFP status were observed for EMG amplitude.

### VMO–VL correlation by surface EMG

Figure 3 shows representative cross-correlation curves across fatigue phases. Both NI-F and NI-M groups demonstrated visible increases in correlation magnitude as fatigue developed, whereas PFP groups exhibited smaller increases. No significant group differences were observed during Phases 1–3.

Figure 4 presents group means for peak correlation and integrated correlation strength (ICS). For peak correlation, there was a significant main effect of fatigue ($p<0.001$), as well as fatigue × group ($p<0.001$) and fatigue × sex ($p=0.009$) interactions. Peak correlation increased progressively across phases (Phase 2-1 = 0.056 ± 0.010; Phase 3-2 = 0.048 ± 0.010; Phase 4-3 = 0.095 ± 0.010; all $p<0.001$). In Phase 4, peak correlation was lower in individuals with PFP compared with controls (mean difference = 0.099 ± 0.013; $p<0.001$), and lower in females than males (mean difference = 0.048 ± 0.013; $p=0.007$). No significant group differences were observed in Phase 1.

For ICS, there was a significant main effect of fatigue ($p<0.001$), as well as fatigue × group ($p=0.002$) and fatigue × sex ($p=0.040$) interactions. ICS demonstrated a progressive increase across fatigue phases, with post hoc analysis indicating a significant increase between Phases 3 and 4 (Phase 4-3 = 0.495 ± 0.10; $p<0.001$). In Phase 4, ICS was lower in PFP compared with controls (mean difference = 0.256 ± 0.112; $p=0.028$) and lower in females than males (mean difference = 0.547 ± 0.166; $p=0.036$).

### VMO–VL correlation by intramuscular EMG

Supplementary Figure S2 presents cross-correlation indices derived from intramuscular EMG. For peak correlation, there was a significant main effect of fatigue ($p<0.001$). Intramuscular peak correlation increased across phases (Phase 2-1 = 0.035 ± 0.009, $p<0.001$; Phase 4-3 = 0.026 ± 0.009, $p=0.020$). No significant main effects of group or sex were observed.

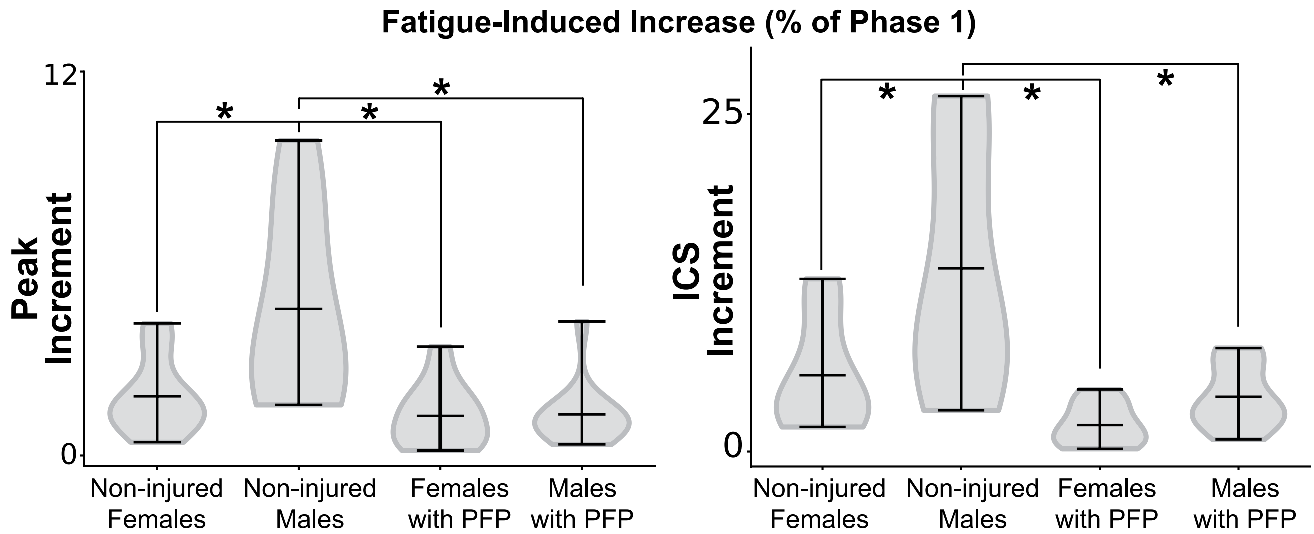


**Fig. 5** Fatigue-induced increases in VMO–VL surface EMG cross-correlation. Violin plots of normalized fatigue-induced changes (Phase 4-Phase 1) in peak correlation (left) and ICS (right). Non-injured males demonstrated greater fatigue-related increases compared with other groups (* $P<0.05$), indicating stronger scaling of activation similarity under sustained load

For ICS, there was a significant main effect of fatigue ($p<0.001$) and a fatigue × group interaction ($p=0.011$). ICS increased with fatigue (Phase 4-3 = 0.558 ± 0.132; $p<0.001$). In Phase 4, individuals with PFP showed lower ICS values than controls (mean difference = 0.960 ± 0.216; $p<0.001$). No significant sex effects were detected for intramuscular measures.

### Fatigue-induced increases in VMO–VL correlation

Normalized fatigue-induced changes (Phase 4-1) are shown in Figure 5. Significant group differences were observed for normalized peak correlation and ICS (both $p<0.001$). Non-injured males demonstrated larger fatigue-induced increases than the other groups. For peak correlation: NI-M = 4.6 ± 2.9; NI-F = 1.9 ± 1.1 ($p=0.003$); PFP-F = 1.2 ± 1.0 ($p<0.001$); PFP-M = 1.3 ± 0.9 ($p<0.001$). For ICS: NI-M = 13.6 ± 8.8; NI-F = 5.7 ± 3.9 ($p=0.004$); PFP-F = 2.0 ± 1.5 ($p<0.001$); PFP-M = 4.1 ± 2.2 ($p<0.001$).

## Discussion

Patellofemoral pain has been associated with altered VMO–VL activation patterns under non-fatigued conditions, but their behavior during progressive fatigue has not been well characterized. The present study demonstrates that VMO–VL EMG cross-correlation increases with fatigue in healthy individuals, whereas this adaptive increase is attenuated in individuals with PFP and in females. Importantly, no group differences were observed at baseline, indicating that differences emerged specifically under fatigued conditions. These findings suggest a reduced capacity to adjust VMO–VL activation similarity during sustained load in PFP.

### Addressing potential crosstalk

Given the anatomical proximity of the VMO and VL, potential crosstalk was carefully considered. Wide intermuscular electrode spacing, low zero-lag correlations of raw signals (<0.1), and the inclusion of intramuscular recordings collectively indicate minimal influence of volume conduction on the cross-correlation measures. Although surface EMG cannot completely eliminate volume conduction, the consistency of fatigue-related trends across recording modalities supports a physiological basis for the observed patterns.

### EMG modalities and metrics considerations

Both surface and intramuscular recordings demonstrated fatigue-related increases in VMO–VL cross-correlation; however, interaction patterns differed by modality and metric. Surface EMG showed significant fatigue × group and fatigue × sex interactions, whereas intramuscular EMG primarily demonstrated a fatigue main effect, with group differences evident mainly in integrated correlation strength (ICS) rather than peak correlation. These differences likely reflect methodological scale and metric sensitivity. Surface EMG captures activity across a broader muscle region and may therefore detect more global differences between groups. In contrast, intramuscular EMG samples a localized motor unit population and may reflect region-specific activation behavior.

Peak correlation represents maximal temporal alignment at a single lag, whereas ICS reflects the overall magnitude of correlated activation across the window. The finding that intramuscular peak correlation was not group-sensitive, while ICS was, suggests that group differences may be more evident in sustained correlation magnitude rather than transient alignment. In addition, although ICS demonstrated a significant overall fatigue effect, post hoc differences were most evident between the final two fatigue phases. This pattern may indicate that changes in the overall magnitude of correlated activation become more pronounced as fatigue approaches task failure, whereas peak correlation appears more sensitive to progressive changes across the entire fatigue process. Together, these results indicate that both recording modality and analytic metric influence the aspects of VMO–VL cross-correlation detected during fatigue.

### VMO–VL cross-correlation and fatigue

Coordinated activation of quadriceps synergists has been proposed to contribute to regulation of mediolateral patellofemoral forces(Barroso et al. 2019; Alessandro et al. 2020). Previous studies have reported increased cross-correlation or coherence between vasti muscles during sustained contractions in healthy individuals(Chang et al. 2012). The present findings extend this work by demonstrating progressive increases in time-domain cross-correlation across fatigue phases in non-injured participants. In contrast, individuals with PFP exhibited smaller fatigue-related increases despite similar pre-fatigue values. These results indicate that differences were not present at rest but emerged as fatigue progressed, suggesting altered adaptation of VMO–VL activation similarity under sustained load in PFP.

Reduced fatigue-related increases in cross-correlation may reflect altered neuromuscular adaptation during prolonged activity. In this context, fatigue appears to function as a physiological stressor that reveals differences not evident under unfatigued conditions. Clinically, evaluating quadriceps function under fatigued states may provide additional insight beyond assessments performed at rest.

### Sex differences

Females demonstrated smaller fatigue-related increases in VMO–VL cross-correlation compared with males. Although underlying mechanisms cannot be determined from the present data, sex differences in fatigability and neuromuscular activation have been previously reported(Hunter 2016). These findings suggest that sex may influence how activation similarity between synergists adapts during sustained load. Further investigation is needed to determine whether such differences reflect task strategy, muscle morphology, hormonal influences, or other neuromuscular factors.

### EMG amplitude versus cross-correlation

EMG amplitude of both the VMO and VL increased with fatigue but did not differ by group or sex. Thus, group differences were not attributable to overall activation magnitude. Cross-correlation of EMG amplitude envelopes captures similarity in activation timing across muscles and provides information complementary to amplitude measures. The present results highlight that VMO–VL cross-correlation may detect differences not apparent through amplitude-based metrics alone.

### Functional role of the VMO

Although the VMO is anatomically continuous with the vastus medialis, regional differences in activation have been reported (Tenan et al. 2016; de Souza et al. 2018). Because the VMO contributes to medial patellar stabilization, examining VMO–VL cross-correlation, rather than global VM–VL activity, provides a more specific window into joint-stabilizing function.

#### Limitations

Several limitations should be acknowledged. The sustained isometric task may not represent dynamic or sport-specific activities. The 20% MVC intensity was selected to allow progressive fatigue with minimal discomfort; different intensities may produce different cross-correlation responses. Intramuscular EMG samples a localized region and does not capture whole-muscle activation. Finally, although multiple procedures were used to minimize crosstalk, surface EMG cannot fully eliminate volume conduction effects.

## Conclusion

Using both surface and intramuscular EMG, this study demonstrates that VMO–VL cross-correlation increases with fatigue in healthy individuals but shows a reduced fatigue-related increase in individuals with PFP and in females. These findings indicate diminished scaling of activation similarity under sustained load in PFP and support fatigue as a useful stress condition for evaluating quadriceps function.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s00421-026-06381-9.

**Acknowledgements** The authors thank the participants for their time

and effort.

**Author contributions** LG and ZW conceived and designed research. ZW conducted experiments, analyzed data and wrote the first draft of the manuscript. LG edited the manuscript. All authors read and approved the manuscript.

## Declarations

**Conflict of interest** The authors declare no conflicts of interest.



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