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*Case Report*

# Trunk and Thigh Coupling During a Lateral Step-Down in Athletes with Patellofemoral Pain: A Case-Control Study

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## Abstract

Background: The coupling pattern and coupling variability between the trunk and thigh may contribute to the mechanism underlying Patellofemoral Pain (PFP).

Materials and Methods: We examined these two variables in a repetitive lateral step-down test in athletes with PFP. The coupling pattern between the trunk and thigh were measured using vector coding, based on the relative motion between the markers on the shoulder and the knee. Trial-to-trial coupling variability was measured using the coefficient of correspondence.

Results: In both contralateral-ipsilateral and anterior-posterior directions, trunk-thigh coupling patterns were similar between PFP and control groups across all bins. Vector angles indicated contralateral trunk lean with knee abduction in the frontal plane and trunk forward lean with knee flexion in the sagittal plane. No significant between-group differences were found in coupling patterns. Coupling variability was largely comparable, except in bin 6 of the contralateral-ipsilateral direction, where the PFP group showed greater variability ($t(18) = -2.6$, $p = 0.02$, Cohen's $d = 0.9$). No significant differences were observed in anterior-posterior variability.

Discussion: The increased variability observed in the patellofemoral pain group could indicate a release of degrees of freedom to reduce repetitive loading at the knee.

**Keywords:** Vector Coding; Coupling; Variability; Relative Motion; Patellofemoral Pain

## Introduction

Patellofemoral Pain (PFP), also referred to as anterior knee pain, is a frequently reported overuse injury in physically active individuals and athletes [1-3]. PFP is defined as pain around or behind the patella, which is aggravated by at least one activity that loads the patellofemoral joint during weight bearing on a flexed knee (e.g., squatting, stair ambulation, jogging/running, hopping/jumping) [4]. PFP occurs in approximately 22.7% of the general population and in 28.9% of adolescents [5]. The prevalence is approximately two times higher in females than males [6]. PFP appears to be multifactorial in nature and is associated with proximal, distal and local contributing factors leading to increased patellofemoral loading and pain [7,8].

Trunk movement is a potential proximal factor that influences patellofemoral loading and pain [9]. A trunk lean towards the affected leg in the frontal plane can bring the ground reaction force vector lateral to the knee and in turn increase valgus stress. The valgus stress can consequently change the dynamic Q (quadriceps) angle, leading to changes in patellofemoral alignment and distribution of joint loading. Despite the potential clinical importance, trunk control has been inadequately investigated in individuals with PFP. A study found that in a single-leg squat on the affected side, individuals with PFP showed increased ipsilateral trunk lean, along with increased contralateral pelvic drop, hip adduction and knee abduction (increased Q angle) compared to their pain-free counterparts [9]. The authors suggested that the increase in ipsilateral trunk lean is a compensatory strategy for the weak hip abductors in the affected side, which is often observed in individuals with PFP [9-11].

While this previous study provided initial evidence that PFP may be associated with altered trunk control, it examined the kinematics of the trunk and lower limb individually as separate units [9]. An important aspect of motor control is to reduce redundant degrees of freedom by coupling multiple body segments as one unit [12,13]. For example, in a balance activity such as single-leg stance, the trunk and leg must coordinate with each other to keep the body center of mass within the base of support. From the perspective of dynamical systems theory, patellofemoral pain could be a "control parameter" that induces an alteration in the inter-segmental coupling pattern. To our best knowledge, the coupling pattern between the trunk and leg has not been investigated in individuals with PFP. Understanding how the coupling pattern is associated with PFP may contribute to the assessment and rehabilitation of this condition. In particular, the trunk and the thigh are directly linked above the knee joint. An alteration of coupling pattern between the trunk and thigh is likely to affect knee loading and alignment, which can in turn may contribute to PFP. Examining the variability of the coupling pattern can generate further insights into how the body system addresses redundant degrees of freedom. The variability indicates how consistently the coupling pattern can be generated repetitively over time. Traditionally, variability is considered movement error where the motor control system cannot generate the same pattern repeatedly; error that should be reduced or eliminated as an intervention. In contrast, the dynamical systems theory suggests that the variability shows the motor control system is adaptable and can generate multiple strategies to achieve the same movement goal, Hamill, et al., applied the dynamical systems theory to explain the underlying mechanism of overuse injuries such as PFP [14,15]. Specifically, overuse injuries may be more likely to occur in people with low movement variability as it increases the frequency of loading on the same body regions causing injury or pain.

This study aimed to investigate the trunk-thigh coupling pattern and its variability in individuals with PFP compared to healthy controls using a dynamical systems theory framework. Specifically, the purpose of this study was to (a) determine whether the trunk-thigh coupling pattern during a repetitive lateral step-down task differs between individuals with PFP and healthy controls and to (b) examine whether the variability of trunk-thigh coupling is different between individuals with PFP and healthy controls. We hypothesized that (a) the trunk-thigh coupling pattern would be altered in the PFP group compared to healthy controls and (b) individuals with PFP will show higher variability in trunk-thigh coupling compared to healthy controls.

## Methodology

### *Participants*

We recruited 10 participants with PFP (6 females and 4 males) and 10 gender-matched healthy controls (non-PFP) using convenience sampling. All participants were athletes engaged in organized sport or athletic activity at least three times per week for 5-10 hours weekly. Individuals with PFP were included if they (a) reported anterior knee pain of at least four weeks' duration and (b) demonstrated pain on at least one clinical test: palpation of the medial or lateral patellar facets, compression of the patella into the trochlear groove with or without quadriceps contraction, or resisted knee extension at 60° of flexion [4]. Healthy controls were required to be free of anterior knee pain and any musculoskeletal or neuromuscular conditions. A licensed physical therapist performed the screening tests for all participants. Exclusion criteria for both groups included (a) a history of knee surgery, major lower extremity injury within the past 12 months, (b) other knee pathologies (e.g., ligament injury, meniscal tear, patellar tendinopathy, osteoarthritis), (c) systemic or neurological disorders affecting movement, (d) inability to perform the lateral step-down test, or contraindication to physical activity. The study protocol was approved by the Institutional Review Board at Northeastern University and all participants provided written informed consent prior to enrollment.

### *Procedures*

All participants were asked to perform the lateral step-down test repetitively over a one-minute period [16]. They were asked to stand on a step on their tested leg and lower their non-tested foot to lightly touch the ground and then return to the starting position, while keeping their arms placed across their chest (Fig. 1). To ensure appropriate knee flexion in the stance leg, researchers used a goniometer to determine if the participants reached 60-65 degrees of knee flexion at their lowest point of the lateral step down before data collection began (Fig. 1). When a participant could not reach the required knee flexion range, the height of the step was adjusted. The affected leg was tested for the PFP group and the dominant leg was tested for the non-PFP group. All participants had a few practice trials before the actual test. During the actual test, we used a metronome set at 40 beats per minute, to ensure the rate of the step-down activity was approximately 20 cycles per minute. The participant performed the downward motion on one beat and the upward motion, returning to the start position on the second beat (1 complete cycle). We only examined the downward motion as the upward motion was not clinically meaningful.

*Instrumentation*

Reflective markers were placed to capture trunk and thigh motion during the lateral step-down test on the acromion process, bilateral greater trochanters, the lateral femoral condyle, the lateral malleolus of the test side and the 5th metatarsal head bilaterally. On the test side, marker on the acromion process was used to track distal trunk motion and marker on the lateral femoral epicondyle was used to track distal thigh motion (Fig. 1). Coupling and coupling variability between the trunk and thigh were quantified based on the relative motion of these two markers. The marker on the lateral malleolus of the non-test side was used to define the step-down cycle, in which the cycle began when this marker reached its highest point and ended at its lowest point. Marker trajectories were recorded using an optical motion capture system (Qualisys AB, Sweden) at a sampling frequency of 100 Hz.

*Outcome Variables*

At baseline, all participants completed the Numerical Pain Rating Scale (0-10) to assess pain severity and the Lower Extremity Functional Scale (0-80) to evaluate functional impairment [17]. The primary outcome measures were (1) the coupling pattern between the distal trunk and distal thigh on the test (stance) side and (2) the variability of this coupling pattern. Both variables were quantified in the contralateral-ipsilateral and anterior-posterior directions. For reference, an ipsilateral shift was defined as movement toward the test/stance side during the lateral step-down test, whereas a contralateral shift indicated movement toward the opposite side. A contralateral shift of the distal femur on the stance leg reflected increased knee valgus, while an anterior shift of the distal trunk or thigh represented flexion.

For the lateral step-down activity, analysis was performed on the first 10 consecutive trials. Because trial durations varied, the number of data points in each position trajectory also differed. To standardize data for comparison, each trial was time-normalized by interpolating to 200 data points prior to calculating coupling patterns and their variability.

The vector coding technique was used to quantify the coupling pattern between the distal trunk (acromion marker) and the distal thigh (the lateral epicondyle marker position) [18,19]. We first plotted the relative motion between the two segments on a XY plot, with the trunk on the X axis and the thigh on the Y axis (Fig. 2). The relative motion was then quantified (see eq.1) with vector angle ϴ, which is an angle subtended from a vector adjoining two successive time points in relation to the right horizontal:

Equation 1

$$\Theta_{j,j+1} = arctan\frac{(Y_{j+1}-Y_j)}{(X_{j+1}-X_j)} \text{ (eq.1),}$$

where j indicates a frame within the time series.

Vector angles were then averaged across the 10 selected trials at each of the 200 time points for each participant, to represent the central tendency of the pattern. Because vector angle is a directional variable, circular statistics were used for calculating the mean (and other descriptive statistics) throughout the study. A vector angle is a circular variable that could run between $0^{\circ}$ or $360^{\circ}$. The coupling pattern represented by the vector angle in each quadrant was presented in Fig. 3. The distal trunk motion may be more, less, or equal to the distal thigh in each quadrant and they will be reflected in different vector angles. For example, A vector angle of $0^{\circ}$ or $180^{\circ}$ indicates that there was trunk motion but no thigh motion. A vector angle of $90^{\circ}$ or $270^{\circ}$ indicates there was thigh motion but no trunk motion. A vector angle of $45^{\circ}$, $135^{\circ}$, $225^{\circ}$ and $315^{\circ}$ indicates that the trunk and thigh motions were equal. The coefficient of correspondence, r (see eq.2), was used to measure coupling pattern variability across the 10 trials at each of the 200 time points. The procedures to calculate r was reported previously in detail [19].

Equation 2

$$r_{j,j+1} = a_{j,j+1} * m_{j,j+1} \text{ (eq.2),}$$

where $a_{j,j+1}$ indicates the variability of vector direction from time frame j to j+1, and $m_{j,j+1}$ indicates the variability of vector magnitude.

We then reversed the direction of r to present on a range from 0 (no variability) to 1 (maximum variability) [20]. Each lateral step-down trial was evenly divided into 10 bins (20 frames/bin) and vector angles and coefficients of correspondence were averaged within each bin for statistical analysis.

*Statistical Analysis*

Data were analyzed using Oriana v4.02 (Kovach Computing Services, Wales, UK) and SPSS v25 (IBM, Armonk, NY). In both the contralateral-ipsilateral and anterior-posterior directions, vector angles (coupling patterns) within each bin were compared between the PFP and control groups using the Watson-Williams circular test. Coupling variability, quantified as coefficients of correspondence, was compared between groups using independent t-tests. The assumptions of normality and homogeneity were assessed with the Shapiro-Wilk test and Levene's test, respectively. Statistical significance was set at $\alpha = 0.05$. To complement p-values, additional effect sizes (Cohen's d) were calculated for significant results and interpreted according to Cohen's guidelines [21].

## Results

*Study Sample*

The PFP and control groups did not differ significantly in age (21.4 ± 2.2 vs. 21.3 ± 1.4 years), height (1.7 ± 0.1 m vs. 1.7 ± 0.1 m), weight (67.0 ± 14.7 kg vs. 69.4 ± 10.9 kg), or BMI (22.5 ± 3.4 vs. 23.0 ± 1.7), as determined by independent t-tests (all p-values > 0.05). The mean pain rating was 3.3 ± 1.7 in the PFP group and 0 in the control group. Functional status, assessed by the Lower Extremity Functional Scale, averaged 69.4 ± 5.0 in the PFP group compared with 79.8 ± 0.7 in the control group.

*Contralateral-Ipsilateral Shift*

Fig. 4 shows the coupling pattern between the distal trunk and distal thigh in the contralateral-ipsilateral direction of the PFP and non-PFP groups. On average, both groups' vector angles were in the first quadrant throughout the 10 bins, indicating that the acromion marker and the lateral femoral marker both have a contralateral shift. This reflects a coupling pattern of trunk contralateral lean and knee abduction (i.e., increase in knee valgus). Some between-group differences in the mean vector angles were observed in each bin, but none of them reached statistical significance ($p > 0.05$).

Fig. 4 shows the coupling pattern variabilities between the distal trunk and distal thigh in the contralateral-ipsilateral direction of the two groups. The variabilities were very close between the groups in each bin. A statistically significant difference was found in bin 6, with the PFP group showed greater variability, $t(18) = -2{,}6$, $p = 0.02$., Cohen's d = 0.9 (a large effect).

*Anterior-Posterior Shift*

Fig. 5 shows the coupling pattern between the distal trunk and distal thigh in the anterior-posterior direction of the PFP and non-PFP groups. On average, both groups' vector angles were in the second quadrant in the first 2 bins, indicating that the acromion marker shifted posteriorly and the lateral femoral marker shifted anteriorly in the beginning of the lateral step down. After the 3rd bin, both groups' vector angles were in the first quadrant, indicating that both acromion and lateral femoral markers shifted anteriorly.

This reflects a coupling pattern of trunk forward lean and knee flexion. Although some between-group differences in the mean vector angles were observed in each bin, none of them reach statistical significance ($p > 0.05$). Fig. 5 shows the coupling pattern variabilities between the distal trunk and distal thigh in the anterior-posterior direction of the two groups. We did not find any significant between-group difference in the variability in any bin ($p > 0.05$).

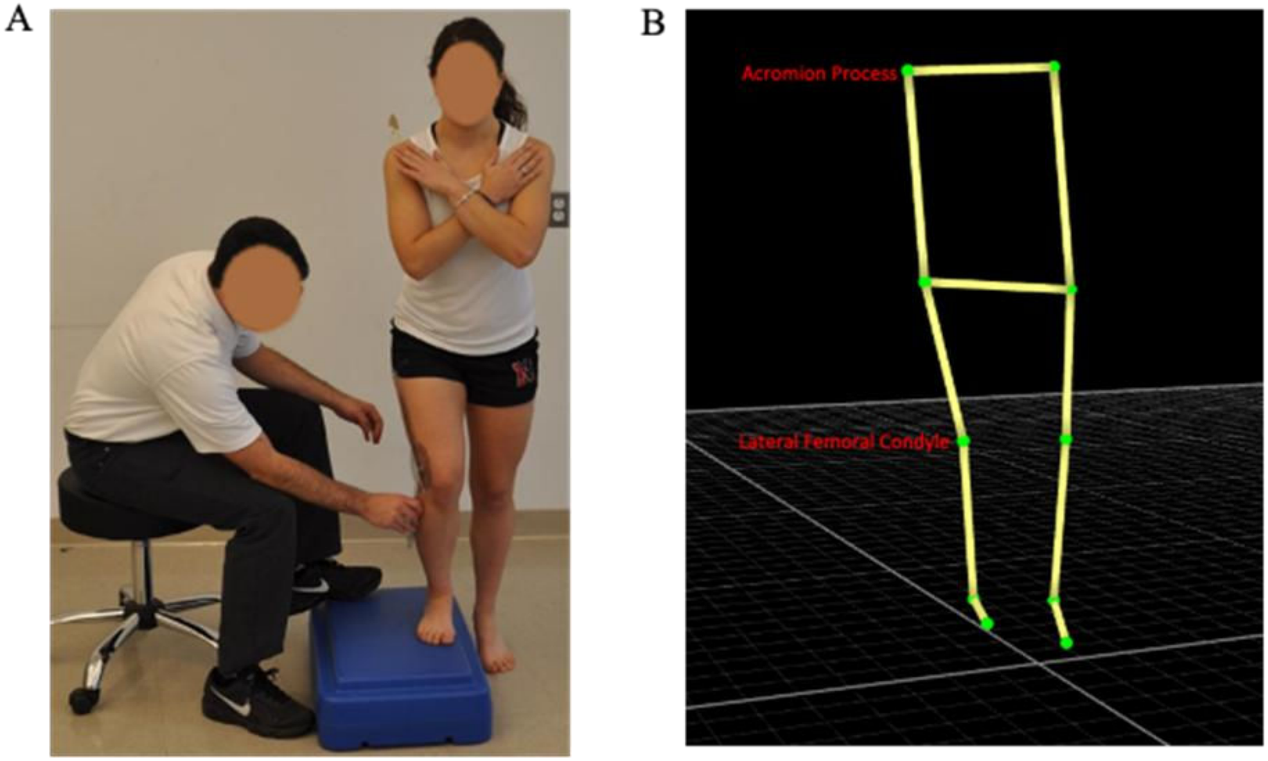


**Figure 1:** (A) The lateral step-down test; (B) Marker placement.

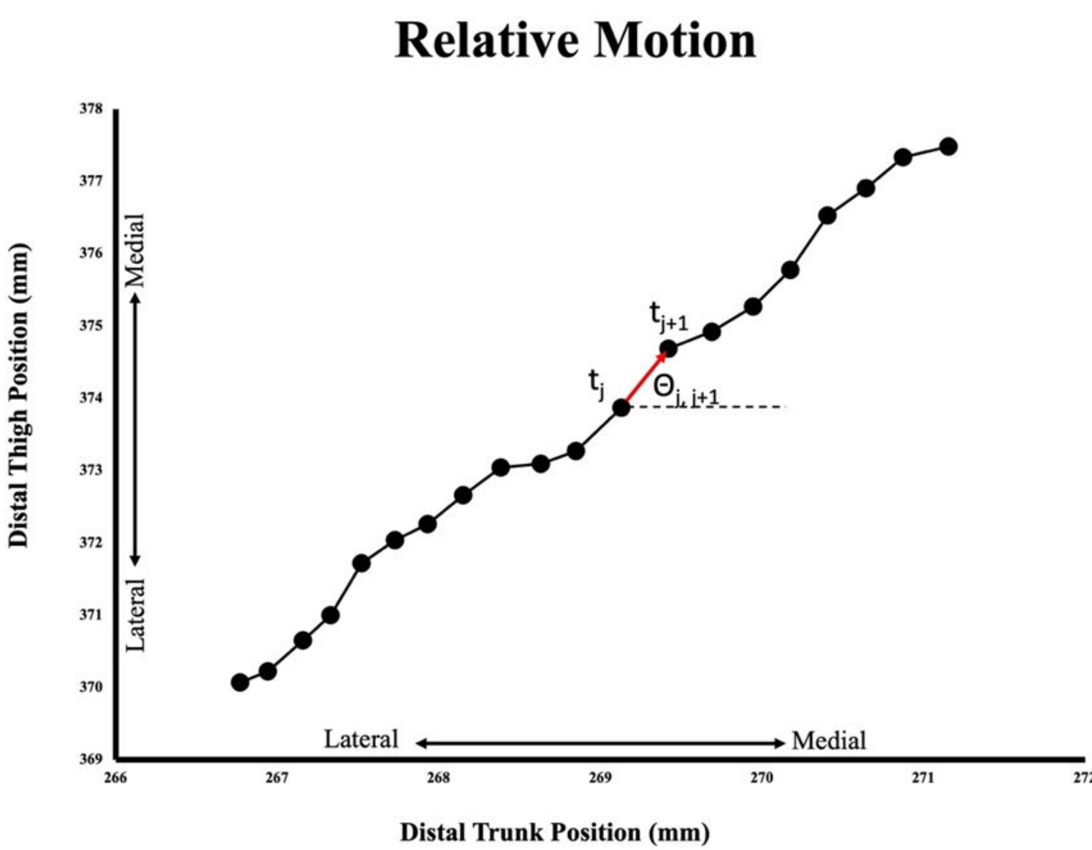


**Figure 2:** Relative motion between the two segments on a XY plot, with the trunk on the X-axis and the thigh on the Y-axis. The relative motion was then quantified with vector angle Θ, which is an angle subtended from a vector adjoining two successive time points in relation to the right horizontal.

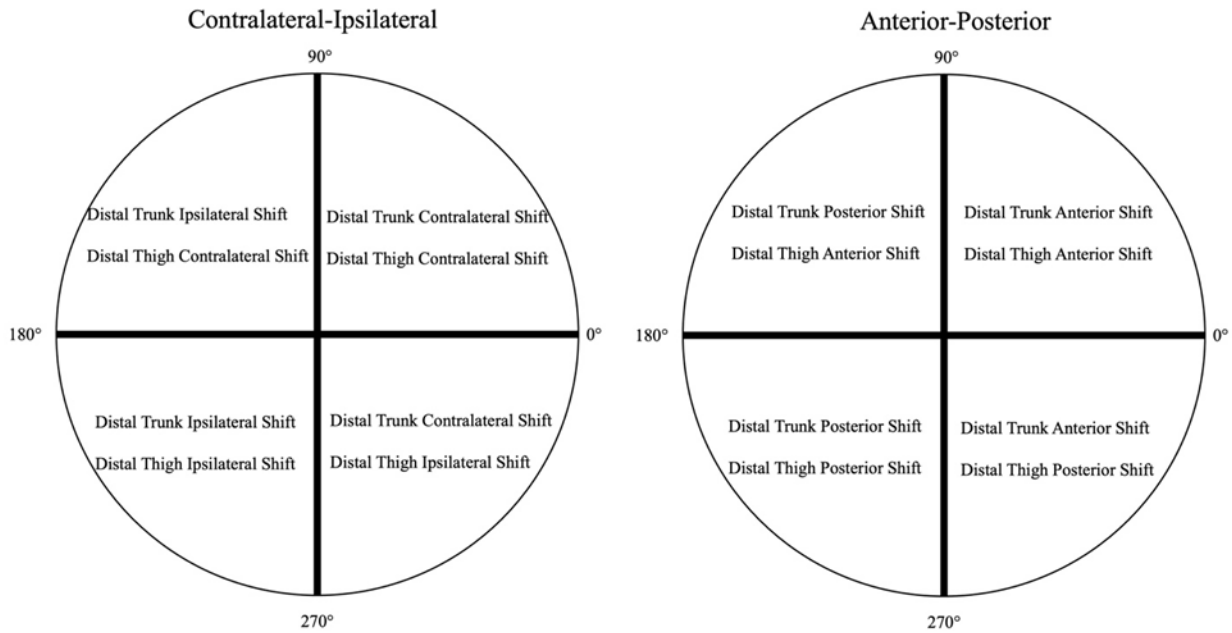


**Figure 3:** The coupling pattern represented by the vector angle in each quadrant.

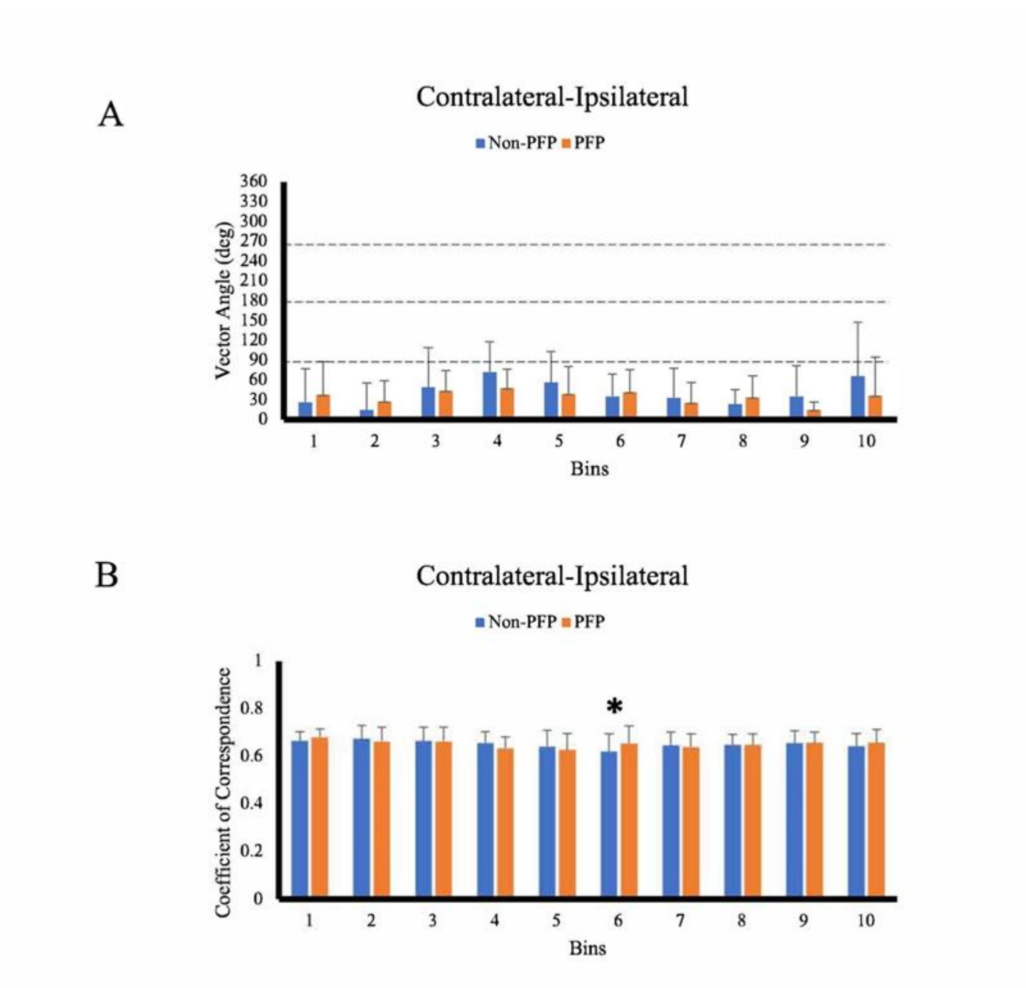


**Figure 4:** (A) Coupling pattern between the distal trunk and distal thigh in the contralateral-ipsilateral direction of the PFP and non-PFP groups; (B) Coupling pattern variabilities between the distal trunk and distal thigh in the contralateral-ipsilateral direction of PFP and non-PFP groups. * = $p < 0.05$.

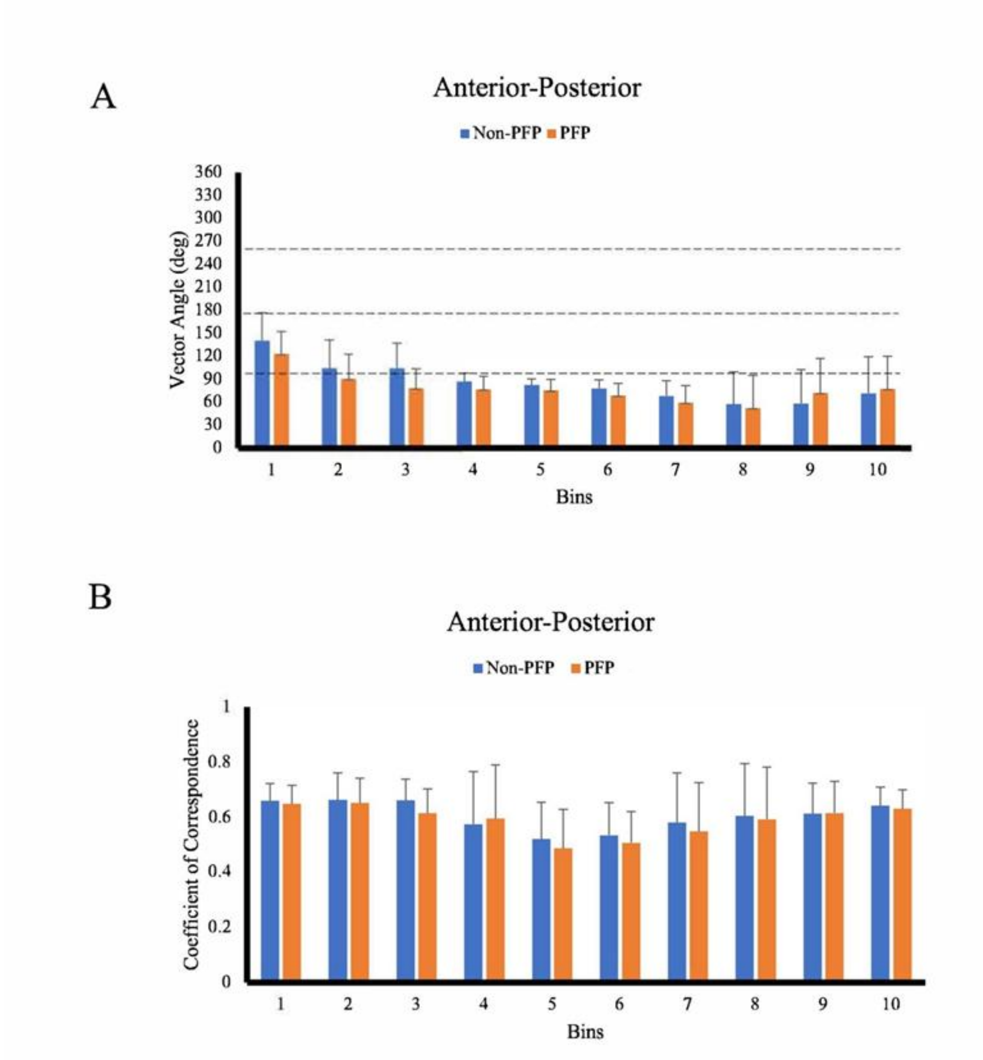


**Figure 5:** (A) Coupling pattern between the distal trunk and distal thigh in the anterior-posterior direction of the PFP and non-PFP groups; (B) Coupling pattern variabilities between the distal trunk and distal thigh in the anterior-posterior direction of PFP and non-PFP group.

**Discussion**

In this study, we aimed to understand whether the coupling pattern and coupling variability between the trunk and thigh may contribute to the mechanism underlying PFP. We compared the coupling pattern and coupling pattern variability between the distal trunk and distal thigh between individuals with and without PFP during a repetitive lateral step-down test. We did not find these variables to be substantially different between the two groups. The only difference that reached statistical significance was the coupling variability in the middle of the lateral step down (50% - 60% of the trial) in the contralateral-ipsilateral direction. The coupling patterns were essentially the same between the groups.

The trunk movement in the frontal plane may have a direct impact on the amount of knee valgus stress and in turn alter patellofemoral alignment and loading. Using single-leg squat as a test, Nakagawa, et al., found that participants with PFP showed significantly greater ipsilateral trunk lean towards the stance/test leg, potentially to compensate for weak hip abductors in the same side [9]. Motivated by their study, we took it one step further by examining if the coupling pattern between the distal trunk and distal thigh was altered in those with PFP, but we did not find any significant results. A major difference between Nakagawa, et al. and this current study was that they used a single-leg squat test and we used a lateral step-down test [9]. Our original thought was that the lateral step-down test involves more frontal plane motion and may be a better task to induce contralateral-ipsilateral shift. However, in the single leg squat test, the contralateral leg is always unloaded and individuals with PFP are more likely to use trunk ipsilateral lean as a compensation for weak hip abductors. In contrast, the lateral step-down test requires the contralateral leg to descend and contact the ground, which naturally shifts the trunk toward the contralateral side without requiring ipsilateral compensation. This difference in task demands may explain why we did not observe different coupling patterns in the ipsilateral-contralateral direction between groups.

The relatively mild pain severity in our PFP cohort represents another possible explanation for the lack of significant differences in coupling patterns. Our PFP participants reported average pain levels of 3.3 ± 1.7/10, which falls at the lower end of the scale despite exceeding the clinically meaningful change threshold of 2 for PFP [24]. This modest pain severity could also explain why between-group differences were only found during one specific period and in one direction. Previous research comparing lower limb coupling variability during running in individuals with and without PFP has yielded contrasting results [22,23]. Despite methodological differences between these studies, it is worth noting that the pain levels of the participants were also different [22,23].

Based on the seminal work by Hamill, et al., two research groups examined the variabilities of inter-segmental coupling patterns in the lower limb in individuals with PFP during running and their findings were not consistent [14,15]. Heiderscheit, et al., found that the variability of the thigh-shank coupling in the transverse plane was significantly lower in individuals with PFP compared to healthy controls around heel contact [22]. In contrast, Cunningham, et al., found that several variabilities of inter-joint coupling patterns in the lower limb were significantly greater in individuals with PFP [23]. Their interpretation was that in individuals who already developed the injury, the increased variability could be a motor strategy to reduce stress among inflamed structures to compensate for the painful state. We also found increased variability in individuals with PFP which could indicate an adaptive motor strategy to avoid repetitive patellofemoral stress.

The motivation for us to investigate coupling variability was because this variable has the potential to become a useful clinical tool to diagnose movement disorders. However, the clinical relevance of variability still needs to be established. In the literature, different studies reported different directions of change in variability in the same condition. Heiderscheit, et al., and Cunningham, et al., were examples in PFP research [22,23]. The specific sample characteristics, the segments/joints investigated, the motor task (e.g., running, lateral step-down, single leg squat) examined, or the measurement tools used could lead to inconsistent findings across studies. To our best knowledge, our study was the first one that investigate trunk-thigh coupling variability in patients with PFP during a lateral step-down test. Similar to Heiderscheit, et al., and Cunningham, et al., we used vector coding to quantify coupling variability [22,23]. For coupling variability, we used coefficient of correspondence to account for the variability of vector direction and magnitude, while Heiderscheit, et al., and Cunningham, et al., used a method based on trial-to-trial standard deviation of the vector angles [22,23].

Cunningham, et al., found that several variabilities of inter-joint coupling patterns in the lower limb were greater in participants with PFP [23]. Their interpretation was that in individuals who already developed the injury, the increased variability could be a motor strategy to reduce stress among inflamed structures to compensate for the painful state. This interpretation could also be applied to explain our results. We found the coupling pattern variability was greater in the PFP group in the contralateral-ipsilateral direction. This could be interpreted as our participants released more degrees of freedom in the middle of the trial to test multiple motor strategies to minimize (avoid) pain. However, it is unclear why the increased variability only happened in the middle of the lateral step-down, but not towards the end of the movement. A previous study found that the patellofemoral stress increases as the knee flexion angle increases during weight bearing knee flexion [24]. If the coupling variability between the distal trunk and distal thigh was increased to reduce stress in the middle of the trial, such increase should have continued towards the end as knee flexion angle and therefore patellofemoral stress kept increasing. This question warrants further investigation in future study.

In this study, we used an acromion marker and a lateral femoral marker to represent the distal trunk and distal thigh, respectively. There are advantages and disadvantages to this method. Measurement errors could be compounded when we use multiple markers to model the trunk and the thigh and use the marker data to calculate angular motion of each segment. These errors could artificially increase the observed coupling variability. Our method is directly based on tracking two markers, which reduces potential measurement error. In addition, the use of two markers to examine anterior-posterior and ipsilateral-contralateral shifts can provide a general picture of relative motion. However, this method would not be able to capture more detailed motion, such as the adaptation in the lower trunk and proximal thigh. Thus, our results must be interpreted with caution.

*Limitations*
This study has several limitations that should be considered when interpreting the findings. First, the small sample size (n = 10 per group) limited statistical power and may have contributed to the lack of significant between-group differences in most outcomes. Second, participants with PFP reported relatively mild symptoms, which may not fully represent individuals with more severe or chronic presentations of the condition. Third, although the lateral step-down test is widely used clinically, it may not have been sensitive enough to elicit compensatory trunk strategies commonly observed in PFP during other tasks such as single-leg squats or running. These limitations highlight the need for future research with larger and more diverse samples, more comprehensive motion analysis and alternative functional tasks to further clarify the role of trunk-thigh coupling in PFP.

## Conclusion
We compared the coupling pattern and coupling pattern variability between the distal trunk and distal thigh between individuals with and without PFP during the lateral step-down test. Based on the results, we concluded that PFP did not alter trunk-thigh coupling during lateral step-down. However, the coupling variability was increased in the middle of the lateral step down (50% - 60% of the trial) in the contralateral-ipsilateral direction. The increased variability could indicate a release of degrees of freedom to reduce repetitive loading at the same location of the knee.

## Conflict of Interest
The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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## Data Availability Statement
Not applicable.

## Informed Consent Statement
Informed consent was taken for this study.

## Authors' Contributions
SY, MC, KC and IW provided consultation including concept, writing and manuscript review. SY provided research design and statistical analysis. MC and SY provided project management.

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