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ORIGINAL ARTICLE

Coordination Variability During Walking and Running in Individuals With and Without Patellofemoral Pain Part 1: Lower Limb Intersegmental Coordination Variability

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Abstract

Purpose Although it has been proposed that individuals with patellofemoral pain show less lower limb intersegmental coordination variability, the evidence to support this hypothesis is rare. The purpose of this study was, therefore, to evaluate whether individuals with patellofemoral pain exhibit less intersegmental coordination variability compared with healthy individuals during walking and running. Also, it was hypothesized that increasing task demand would exacerbate group differences regarding coordination variability measures.

Methods Three-dimensional kinematics were collected while 17 females with patellofemoral pain and 17 healthy females walked at preferred speed, and ran at preferred and fixed speed on a treadmill, each trial for 30 seconds. An approach involving Hilbert transform was used to quantify the Continuous Relative Phase as a method to calculate the coordination variability of the thigh-shank and shank-foot couplings in different motion planes during stance and swing. Intersegmental coordination variability was compared between groups during 3 gait trials using a mixed-model repeated-measures ANOVA.

Results The patellofemoral pain group was significantly less variable compared with the control group in the following couplings: thigh sagittal-shank transverse, thigh transverse-shank transverse, shank transverse-foot sagittal, shank sagittal-foot transverse at both running speeds, thigh frontal-shank transverse at preferred speed running, and shank transverse-foot transverse at fixed speed running, all during stance phase. No between-group difference was observed during walking. Only the patellofemoral pain group showed changes in coordination variability by increasing task demand, in a way that they showed less coordination variability at running trials compared with the walking and also at fixed speed compared with the preferred speed running for some of the examined couplings.

Conclusion Based on the results, less lower limb intersegmental coordination variability may be characteristic of females with patellofemoral pain during treadmill running. Increasing task demand from walking to running and also from preferred speed to fixed speed running which mainly resulted from increasing gait speed could exacerbate this altered coordination variability.

Keywords Variability · Coordination · Dynamical system · Overuse injury · Patellofemoral pain

1 Introduction

Despite the high prevalence and recurrence rate of patellofemoral pain (PFP), its exact etiology has not been well diagnosed [1, 2]. Many researchers have attempted to detect kinematic alterations related to PFP. For example, excessive rearfoot eversion and accompanied tibial internal rotation are hypothesized to contribute to patellofemoral (PF) joint dysfunction [3–5]. It is theorized that the lack of tibial external rotation during midstance induced by excessive foot pronation results in greater femoral internal rotation to ensure relative tibial external rotation allowing screw home

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mechanism and normal knee extension [6]. The increased femoral internal rotation would increase the quadriceps angle (Q-angle) and thereby PF joint contact pressure and pain [7]. Excessive tibial abduction or femoral adduction and or a combination of both have also been assumed to increase the knee valgus which in turn influences the PF kinematic and function [5].

Existing research evaluating the kinematics of lower limb joints and segments in individuals with PFP have produced inconsistent results or have failed to show significant differences between PFP and healthy groups. This could be in part because these studies evaluated the kinematic variables of a single joint or segment while it is well known that smooth functional movements like walking and running require the coordination of multiple degrees of freedom (DoF) (joints, segments, etc.) [8, 9]. Bernstein described the coordination as the process of producing movement patterns through mastering the large number of DoF [10] Due to the high number of DoF, variability in the produced coordinative structure is unavoidable which enables the individual to use a variety of solutions to accomplish a particular task [11]. This concept underlies the dynamic system theory (DST) which suggests that the coordination variability allows the system to explore the movement patterns and transit between them, providing flexibility in executing a task or responding to the local and global perturbations. Given this theory, reduced variability which manifests with highly repeatable movement patterns explains the pathologic state of the system [12, 13]. Hamill et al. originally applied the DST perspective to lower extremity orthopedic injuries and investigated intersegmental coordination variability in patients with PFP using the continuous relative phase (CRP) method (a spatiotemporal coordination measure based on phase relation of two oscillating segments) [9]. They theorized that lower intersegmental coordination variability may increase the loading frequency of particular tissues, put repeated stress on the same joint contact area, and over time results in PFP while higher variability distributes the stress by creating multiple goal-directed intersegmental couplings. Subsequently, this concept has been the focus of considerable musculoskeletal research, however, a few numbers of studies investigated coordination variability in patients with PFP, which produced inconsistent findings [14–16]. Using modified vector coding technique (a spatial coordination measure based on the angle-angle plot), Heiderscheit et al. demonstrated that lower limb intersegmental coupling angle variability was not substantially different in patients with PFP compared with healthy controls and only the variability of the coupling between thigh and shank in transverse plane was significantly lesser in individuals with PFP near heel strike [15]. Two other studies were also conducted to investigate the effect of acute pain induced by prolonged running on coupling angle variability (CAV) in patients with PFP using the modified vector coding technique. Contrary to the dynamic system perspective to overuse injuries, Cunningham et al. [14], reported increased CAV for several knee-ankle couplings at the point with the highest pain during a 15-minutes running in patients with PFP compared to controls. Jewel et al. [16], demonstrated decreased CAV in pelvis frontal-thigh frontal at the end compared to the start of the run in the PFP, but not the control group. They also observed greater CAV in PFP compared to the control group at the start of the run which opposed the theory proposed by Hamill et al. [9].

Due to the paucity of research investigating the coordination variability in patients with PFP and also the inconsistent results among the few existing studies, the purpose of the present study was to compare lower limb intersegmental coordination variability between PFP and healthy groups using the CRP method. None of the above-mentioned studies has explored the lower limb intersegmental coordination variability during walking, so the intersegmental coordination variability was compared between groups across both walking and running. It was hypothesized that CRP variability of intersegmental couplings would be less in PFP compared to the control group and this difference would be aggravated by increasing the task demand.

2 Methods

2.1 Participants

This case-control study recruited 34 females aged 18–35 years (17 healthy controls and 17 individuals with unilateral PFP) through advertisements in Shiraz University of Medical Sciences, surrounding community, and social media. The sample size was determined based on data from a previous study [14]. Assuming an effect size of 0.89, power of 80%, and a significance level of 0.05, 17 participants in each group were estimated. A written consent form was signed by all research participants before their participation and ethical approval was granted by the local Ethics Committee of Shiraz University of Medical Sciences (IR.SUMS.REHAB.REC.1397.006). The PFP group inclusion criteria were as follows: insidious onset of peri- or retropatellar pain lasted for at least 3 months, pain provoked by at least 2 of the following activities: running, stair ambulation, prolonged sitting, kneeling, squatting, jumping and hopping, pain evoked by palpation of medial and/or lateral patellar facets, quadriceps isometric contraction or applying a compressive force on the patella, pain intensity of at least 3 in 11-point NRS (0–10), positive patellar apprehension test (sensitivity: 86.7%, specificity: 86.7%) [17] and score less than 85/100 on the Kujala anterior knee pain scale (KAPS) [18]. The PFP group exclusion criteria were as follows: other knee injuries except for PFP such as ligamentous instability, meniscal

pathology, plica syndrome, osteoarthritis, patellar subluxation or dislocation, bursitis, patellar tendonitis, etc., visible lower extremity structural malalignment or other orthopedic conditions which could affect the gait, history of any lower limb inflammatory process or metabolic disease like diabetes, history of cardiovascular pathologies, neurological disease, pregnancy, have received physiotherapy, opiate treatment, acupuncture or oral steroids within past 6 months and professional athletes. The healthy volunteers as the control group did not have any history of lower extremity injury or knee pain. They were matched to the PFP group based on age, height, mass and the evaluated limb side. The other exclusion criteria of the control group were the same as the PFP group.

2.2 Data Acquisition

Kinematic data were collected using an eight-camera, 3-dimensional motion analysis system (Proreflex, Qualisys Medical AB, Gothenburg, Sweden) at a sampling rate of 200 Hz. Walking and running trials were conducted on a level grade treadmill (PROTEUS IMT-8000/8500, Philippines). Consistent with the calibrated anatomical systems technique (CAST) using a 6 DoF model [19], retro-reflective markers were attached to the participant's specific anatomical landmarks by the same investigator to model the thigh, shank, and foot segments: the center of greater trochanters, medial and lateral femoral condyles, medial and lateral malleoli. Reflective markers were also placed on the shoe at the center of the calcaneus, first, second, fifth metatarsal heads, and fifth metatarsal base. Moreover, rigid plates consisting of four markers were wrapped at lateral-distal aspects of thigh and shank, using elastic Velcro. All participants wore the same brand of standard shoes to minimize the footwear-related confounding factors. To determine the preferred speeds of walking and running, while participants were blinded to treadmill speed display, the investigator increased or decreased speed between the range of 0.85 to 1.52 and 2.2 to 3.3 m/s respectively until the participants report a comfortable speed. Moreover, to assess the possible confounding effects of different preferred speeds, the speed of 2.68 m/s was set for the fixed speed running (FSR). The rationale for selecting the above-mentioned speeds is that the reported transition speed between walking and running is near 2 m/s [20].

Participants had enough time to familiarize themselves with walking and running on the treadmill. Before dynamic trials and while the participants performed a standing calibration trial, marker positions were recorded for 3 seconds. 3-dimensional marker trajectories during each dynamic trial were recorded for 30 seconds. All data were collected in a single session with sufficient time in between to avoid fatigue.

2.3 Data Analysis

Qualisys Track Manager software was used to identify and label retroreflective markers. Marker trajectories were exported to Visual3D software (C-Motion®, Rockville, MD, USA) to quantify 3-dimensional segment angles of thigh, shank, and foot. Kinematic data were filtered using a fourth-order Butterworth low-pass filter with a cut-off frequency of 9 HZ. Segment motions were defined relative to the global coordinate system using the X–Y–Z (flexion/extension, abduction/adduction, internal/external rotation) Cardan rotation sequences. To detect heel contact and toe-off events, the vertical displacement algorithm was used based on the horizontal and vertical positions of the reflective marker placed on the shoe at calcaneal tuberosity [21].

A custom written MATLAB program (version 2018a, The MathWorks Inc., Natick, MA) was used to calculate the CRP and CRP variability. First, segment kinematics were interpolated to 100% of a gait cycle, then the range of the desired signal amplitudes was centered around zero using a method suggested by Lamb and Stöckl [22]. CRP represents the difference between phase angles of two segment motions that constitute an intersegmental coupling. In the present study, the phase angle for each time series was calculated based on the real signal itself ($X(t)$) and its Hilbert transform ($H(t)$) [22]. The Hilbert transform creates a complex, analytic signal ($\zeta(t)$) from $X(t)$.

Equation 1:

$$\zeta(t) = X(t) + iH(t) \tag{1}$$

Then the phase angle of each segment angular displacement time series at a given point in time (t) was calculated as:

Equation 2:

$$\phi_x = \tan^{-1}\left(\frac{H(t)}{X(t)}\right) \tag{2}$$

The CRP between two signals ($X_1(t)$ and $X_2(t)$) was then calculated by subtracting the phase angle of two segments signals from each other:

Equation 3:

$$CRP(t) = \phi_1(t) - \phi_2(t) = \tan^{-1}\left(\frac{H_1(t)X_2(t) - H_2(t)X_1(t)}{X_1(t)X_2(t) - H_1(t)H_2(t)}\right) \tag{3}$$

where $H_1(t)$ and $H_2(t)$ represent the Hilbert transform of $X_1(t)$ and $X_2(t)$.

To adjust the discontinuities that occurred due to the arctangent function, the absolute values of the CRP more

than 180 were subtracted from 360. Then, the CRP curves for each intersegmental coupling were averaged across all gait cycles during each dynamic trial and the mean ensemble average curves were generated. Finally, to calculate the intersegmental coordination variability, the deviation phase (DP) was calculated by averaging the standard deviation of the ensembled CRP curve points [23, 24] for both the stance and swing phases of the gait cycle:

Equation 4:

$$DP = \frac{1}{N}\sum_{i=1}^{N}\left|SD_i\right| \tag{4}$$

where N is the number of points in the ensembled CRP curve and SD_i is the standard deviation of the ensembled CRP curve at each point (i). Lower values of DP represent less coordination variability (i.e. more stability) and vise versa. CRP variability was calculated for lower limb intersegmental couples listed in Table 1.

2.4 Statistical Analysis

All statistical analyses were performed with SPSS software (version 21; SPSS Inc., Chicago, IL, USA). An independent t-test was used to compare demographic information between study groups. Intersegmental coordination variability was compared between groups during 3 gait trials (preferred speed walking (PSW), preferred speed running (PSR), and FSR) using a 2 × 3 (Group × Trial) mixed-model repeated-measures ANOVA with the trial as the repeated measure. Post-hoc testing was performed for all significant ANOVA with independent sample t-test (group) or repeated measure ANOVA (trials) with a Bonferroni correction for multiple comparisons. The significance level was set at $p \leq 0.05$.

Table 1 Intersegmental couplings and their abbreviation.

Intersegmental coupling	Abbreviation
Thigh $_{sagittal}$–Shank $_{transverse}$	Ths–Sht
Thigh $_{frontal}$–Shank $_{transverse}$	Thf–Sht
Thigh $_{transverse}$–Shank $_{transverse}$	Tht–Sht
Thigh $_{sagittal}$–Shank $_{sagittal}$	Ths–Shs
Shank $_{transverse}$–Foot $_{transverse}$	Sht–Ft
Shank $_{transverse}$–Foot $_{sagittal}$	Sht–Fs
Shank $_{sagittal}$–Foot $_{transverse}$	Shs–Ft

3 Results

Both PFP and control groups were similar concerning age, height, weight, and preferred speed of walking and running (Table 2). PFP group tended to run with lower speed at PSR compared with the control group (P = 0.057).

Table 3 summarizes the repeated measure ANOVA results for CRP variability of lower limb intersegmental couplings during stance. There was a significant group by trial interactions (P < 0.05) for CRP variability of Ths-Sht, Thf-Sht, Sht-Fs, Sht-Ft, and Shs-Ft during stance (Table 3). Although the interaction effect for CRP variability of Tht-Sht is not significant based on Table 3, the related graph shows some group by trial interaction (Fig. 1). Significant interaction effects were broken down to compare the relevant variables between two groups in each trial and also between 3 trials in each group (Fig. 2): significant group differences were found for Ths-Sht (P = 0.027, P = 0.005), Tht-Sht (P = 0.027, P = 0.016), Sht-Fs (P = 0.028, P = 0.012) and Shs-Ft (P = 0.039, P = 0.027) at PSR and FSR respectively, for Sht-Ft at FSR (P = 0.023) and Tf-St at PSR (P = 0.029), all during stance, with PFP group demonstrating significantly less coordination variability (Fig. 2). The PFP group also tended to be less variable in Thf-Sht at FSR (P = 0.054) compared with the control group (Fig. 2). Pairwise comparisons between trials in each group showed that PFP, not the control group was significantly less variable in Ths-Sht, Sht-Ft, and Shs-Ft during stance at PSR and FSR compared with PSW and at FSR compared with PSR. Significantly less CRP variability of Thf-Sht and Sht-Fs during stance was also seen at PSR and FSR compared with PSW in the PFP group (Fig. 2).

The main effect for group tended to be significant for CRP variability of Shs-Ft during swing, with the PFP group showing less variability compared with the control group (Table 4).

Table 2 Mean ± SD of demographics and preferred speed of walking and running in PFP and control groups

	PFP (Mean ± SD)	Control (Mean ± SD)	*P-value*
Age (yr)	25.94 ± 3.99	24.12 ± 3.90	0.073
Height (m)	1.63 ± 0.05	1.61 ± 0.06	0.442
Weight (Kg)	59.70 ± 10.82	56.38 ± 5.70	0.275
Treadmill velocity during PSW (m/s)	1.02 ± 0.16	1.03 ± 0.13	0.877
Treadmill velocity during PSR (m/s)	2.10 ± 0.10	2.23 ± 0.24	0.057

PFP patellofemoral pain, *PSW* preferred speed walking, *PSR* preferred speed running

Table 3 Intersegmental coordination variability (mean ± SD) and repeated measure ANOVA results during stance in those with and without PFP at three gait trials

		Mean ± SD			Repeated-measure ANOVA results		
	Group	PSW	PSR	FSR	Group × Trial	Group	Trial
					F (P-value)	*F (P-value)*	*F (P-value)*
Ths-Shs	Control	3.37 ± 0.67	3.97 ± 0.52	4.92 ± 1.23	2.04 (0.147)	0.24 (0.626)	35.72 (< 0.001*)
	PFP	3.11 ± 0.66	4.17 ± 0.90	5.31 ± 1.61			
Ths-Sht	Control	15.33 ± 5.64	15.93 ± 5.73	15.79 ± 6.53	4.30 (0.022*)	1.74 (0.196)	3.69 (0.036*)
	PFP	10.49 ± 2.56	12.11 ± 3.67	18.27 ± 9.33			
Thf-Sht	Control	23.04 ± 10.42	24.98 ± 11.33	19.84 ± 6.75	5.14 (0.012*)	1.93 (0.174)	1.68 (0.202)
	PFP	16.99 ± 6.70	17.88 ± 5.45	23.75 ± 6.71			
Tht-Sht	Control	29.96 ±7.52	29.87 ± 6.50	22.43 ± 9.43	1.84 (0.175)	4.41 (0.044*)	1.74 (0.191)
	PFP	24.30 ± 6.61	23.39 ± 8.23	23.64 ± 10.08			
Sht-Ft	Control	15.90 ± 7.85	16.12 ± 7.82	14.97 ± 6.09	4.57 (0.018*)	0.42 (0.518)	3.33 (0.049*)
	PFP	10.99 ± 3.38	13.15 ± 5.00	19.03 ± 10.01			
Sht-Fs	Control	15.84 ± 6.98	15.57 ± 5.78	14.14 ± 5.09	3.96 (0.029*)	1.70 (0.202)	1.21 (0.311)
	PFP	10.86 ± 2.46	11.82 ± 3.37	16.80 ± 8.98			
Shs-Ft	Control	13.47 ± 4.84	15.37 ± 5.57	14.47 ± 5.03	5.01 (0.013*)	1.02 (0.320)	8.25 (0.001*)
	PFP	10.30 ± 2.73	11.88 ± 3.70	16.81 ± 7.06			

PFP patellofemoral pain, *PSW* preferred speed walking, *PSR* preferred speed running, *FSR* fixed speed running

*$P < 0.05$

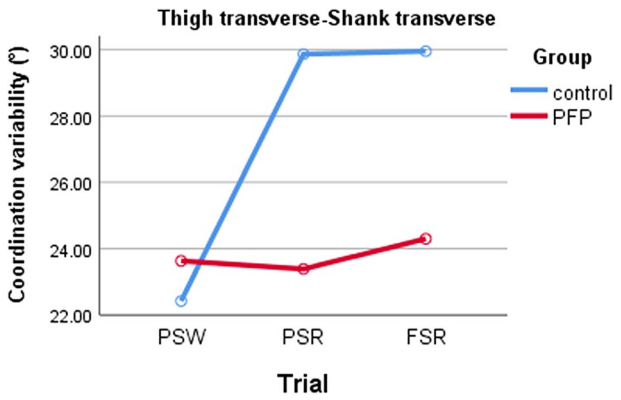

Fig. 1 Line graph showing the significant group by trial interaction for coordination variability of thigh transverse-shank transverse during stance; *PFP* patellofemoral pain, *PSW* preferred speed walking, *PSR* preferred speed running, *FSR* fixed speed running

Significant main effects for trial were found for Ths-Shs during stance (Table 3) and Ths-Shs, Thf-Sht, and Tht-Sht during swing (Table 4). Pairwise comparison between trials showed less coordination variability for Thf-Sht during swing at FSR compared with PSR and PSW, Ths-Shs during stance at FSR and PSR compared with PSW and also at FSR compared with PSR, Ths-Shs during swing at FSR and PSR compared with PSW. Moreover, more coordination variability was seen in Tht-Sht during swing at FSR and PSR compared with PSW.

4 Discussion

The purpose of this study was to compare the variability of lower limb intersegmental coordination between females with and without PFP. In accordance with our hypothesis, results revealed that individuals with PFP were significantly less variable in lower limb intersegmental coordination compared with the control group.

The findings of the present study are in agreement with the DST perspective of overuse injuries. Based on this theory, low variability in the relative phase of two segments or joints is a hallmark of a pathological condition. Accordingly, there are several combinations of intersegmental coordination that a healthy person uses to perform the desired task while the number of these couplings decreases following an injury or pathology, and therefore the coordination variability is greatly reduced [12, 13].

The first application of DST for evaluating an orthopedic injury (PFP) was done by Hamill et al. [9]. They theorized that a higher value of coordination variability is an indicator of a healthy individual and a lower value of coordination variability is an indicator of a patient with PFP. They assumed that the lack of variability in segmental or joint couplings indicates that segment or joint actions are repeated within a narrow range and this enables the patients with PFP to complete the task with minimal pain through avoiding painful patterns.

Lower variability in patients with PFP, however, has been proposed to exert repetitive stress locally on the same

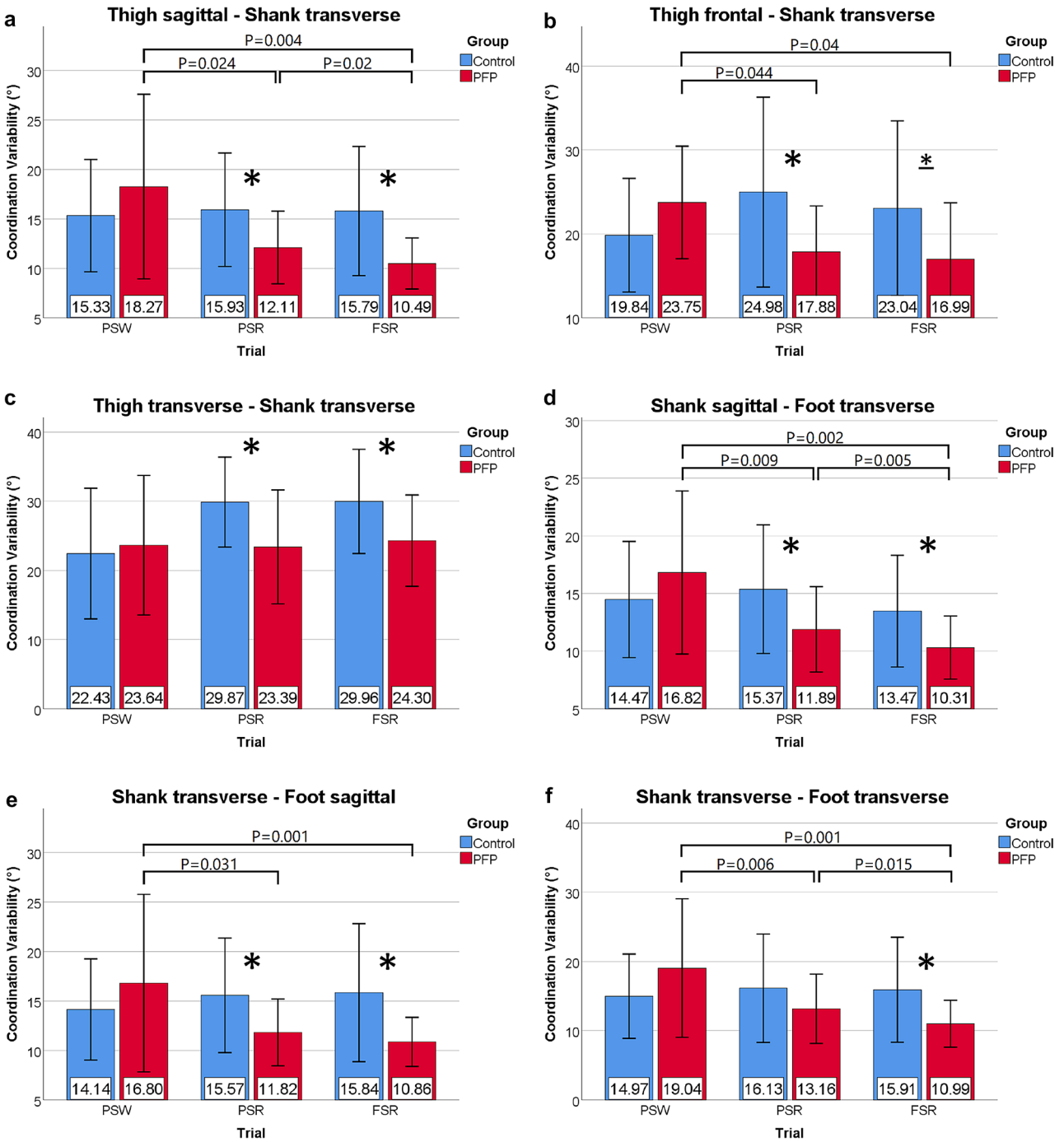

Fig. 2 Bar graphs illustrating the significant interaction between group (control and patellofemoral pain (PFP)) and gait trial (preferred speed walking (PSW), preferred speed running (PSR) and fixed speed running (FSR)) for intersegmental coordination variability during stance: **a** thigh sagittal-shank transverse; **b** thigh frontal-shank transverse; **c** thigh transverse-shank transverse; **d** shank sagittal-foot transverse; **e** shank transverse-Foot sagittal; **f** shank transverse-Foot transverse. Values are represented as mean. Error bars represent the standard deviation of the mean value of the group during that trial. Individual P-values relating to pairwise comparison of trials in the PFP group are indicated above bar graphs. *Significant between-group differences, *group differences tended to be significant

area of cartilage, eventually leading to pain and destructive changes [9, 25], so it does not seem the right solution for longer periods. Moreover, by reducing the number of available movement patterns and thus reducing the flexibility of the system, low variability reduces the ability to respond to external perturbations [26].

The rationale for choosing the intersegmental couplings was based on the kinematic alterations that typically have

Table 4 Intersegmental coordination variability (mean ± SD) and repeated measure ANOVA results during swing in those with and without PFP at three gait trials

	Group	Mean ± SD			Repeated-measure ANOVA results		
		PSW	PSR	FSR	Group × Trial	Group	Trial
					F (P-value)	*F (P-value)*	*F (P-value)*
Ths-Shs	Control	2.80 ± 0.60	3.37 ± 0.74	2.76 ± 0.45	1.34 (0.275)	1.84 (0.183)	3.29 (0.050*)
	PFP	3.46 ± 1.17	3.34 ± 1.32	3.02 ± 0.84			
Ths-Sht	Control	24.99 ± 10.75	29.93 ± 8.17	28.14 ± 8.41	1.26 (0.298)	0.04 (0.831)	0.85 (0.434)
	PFP	27.33 ± 8.61	26.86 ± 9.88	24.14 ± 9.66			
Thf-Sht	Control	29.96 ± 11.88	30.69 ± 6.11	28.63 ± 7.49	2.49 (0.099)	0.53 (0.496)	7.33 (0.002*)
	PFP	36.20 ± 8.07	30.88 ± 10.33	28.06 ± 9.83			
Tht-Sht	Control	22.41 ± 9.43	36.16 ± 8.07	35.47 ±8.12	0.67 (0.517)	0.005 (0.942)	16.34 (<0.001*)
	PFP	23.62 ± 10.08	34.43 ± 8.65	35.53 ± 8.15			
Sht-Ft	Control	31.31 ± 11.74	34.99 ± 8.58	32.03 ± 7.99	1.26 (0.296)	0.90 (0.348)	1.84 (0.175)
	PFP	31.76 ± 10.16	30.07 ± 7.93	28.68 ± 8.91			
Sht-Fs	Control	23.70 ± 11.11	29.80 ± 8.61	27.09 ± 7.96	1.64 (0.209)	0.004 (0.949)	1.17 (0.321)
	PFP	28.02 ± 9.18	27.04 ± 11.22	26.05 ± 8.84			
Shs-Ft	Control	25.09 ± 10.62	28.17 ± 9.52	25.52 ± 7.93	1.01 (0.376)	3.95 (0.055)	1.09 (0.348)
	PFP	21.79 ± 9.52	21.05 ± 8.17	20.87 ± 8.78			

PFP patellofemoral pain, *PSW* preferred speed walking, *PSR* preferred speed running, *FSR* fixed speed running

*$P < 0.05$

been found or theorized in patients with PFP. There is evidence that individuals with PFP exhibit increased femoral adduction [27–30], femoral internal rotation [28, 29, 31], tibial abduction [32], tibial internal rotation [30, 33], and also rearfoot pronation [34, 35] compared to the healthy individuals. They also exhibit differences in tibiofemoral [36] and ankle joint [27] kinematics in the sagittal plane compared to the healthy group. Lower limb kinematic alterations in persons with PFP result in patellar malalignment and maltracking which contribute to the reduced contact area and increased contact pressure of the PF joint [37]. Reduced contact surface of the patellofemoral joint combined with reduced intersegmental coordination variability could accelerate the onset and progression of joint structures wear and tear and therefore PFP.

There are a few studies that have investigated the coordination variability in individuals with PFP which provided inconsistent results [9, 14–16].

In the study by Hamill et al. [9], coordination variability for thigh flexion/extension-tibial rotation, thigh abduction/adduction-tibial rotation, tibial rotation-foot inversion/eversion, and femoral rotation-tibial rotation was compared between symptomatic individuals with PFP and healthy controls using the CRP variability during running at different speeds (2.5, 3, and 3.5 m/s). The variability was lower for all mentioned couplings in the PFP compared to the healthy group during the swing phase and the results were similar for all three speeds. The findings of the present study are consistent with those of Hamill et al. regarding lower coordination variability in PFP compared to the control group; however, contrary to the study by Hamill which found significant between-group differences during the swing phase of the running cycle, in the present study the significant differences in coordination variability between two groups were mostly found in the stance phase. Based on the theory claiming less variability is associated with repetitive tissue stress, lesser coordination variability during the stance phase is more logical, where high tissue stress for an injury such as PFP occurs.

The finding of the present study is also in agreement with the study by Heiderscheit et al. [15]. In this study, modified Vector Coding method was used to evaluate the coordination variability of femoral rotation/tibial rotation, hip flexion/knee flexion, knee rotation/ankle inversion, and knee flexion/ankle dorsiflexion couplings. They found a significant reduction in coordination variability of thigh rotation-leg rotation before heel strikes in the PFP compared to the healthy group during running at preferred speed. Note that the only coupling that showed a significant difference between the two groups in the study by Heiderscheit was thigh rotation-leg rotation, which was the only common coupling with the present study, and the other couplings were between joints, not segments.

However, the results of the present study contradict those of the study by Cunningham et al. [14]. In this study, the coupling angle variability assessed by modified vector coding was higher in the PFP compared to the healthy group in 7 out of the 48 measurements at the beginning of the stance

phase. In this study, the participants ran for 15 minutes at a preferred speed in the range of 2.2 to 3.3 m/s. Data were selected for the patient group when the pain reached the highest point (≥ 3) and the individuals were in a non-exerted state ($< 14/20$), which was on average the 11th minute. Data selection for the healthy group was also done at the 11th minute. Kinematic data were collected from the first 10 seconds of the 11th minute and five non-consecutive stride cycles were selected for analysis. Coupling angle variability was calculated for six knee-ankle couplings at different intervals of a running cycle. They described the increased coupling variability as a form of compensatory strategy for pain induced by exhaustive run which reduces stress on inflamed structures. Therefore, it was concluded that there is an optimal amount of variability and the extreme values (either too much or too little) are harmful to a biological system and can lead to overuse conditions in the lower extremities.

As mentioned above, the measurements of this study were performed discretely from specific times of running cycles and for non-consecutive cycles, which is not the same as the conventional method of other studies as well as the present study. Besides, the couplings assessed in this study were all between two joints, while in the present study, intersegmental couplings were considered. Another possibility for the contradictory results between the study by Cunningham and the present study is that the total running time (warm-up and main test) in this study was 21 minutes and on average the 11th minute of the main test was selected for data collection while in previous studies data were collected for 20 seconds, [9, 15] and in the present study each dynamic trial was performed for 30 seconds. So, running for a longer time might unfold the muscle weaknesses of patients with PFP and/or induce acute pain which can lead to more instability of the segments and joints, and therefore higher movement variability.

In a recent study done by Jewell et al. [16] the effect of PFP on intersegmental coupling angle variability during a prolonged treadmill running (21 minutes) was investigated using modified vector coding. They reported that the variability of pelvis frontal-thigh frontal decreased in the PFP group during midstance at the end of the run, when most runners experienced pain, compared to the beginning. Contrary to the hypothesis proposed by Hamill et al., this study also showed higher thigh sagittal-shank sagittal variability in the weight acceptance of the stance phase in the PFP compared to the healthy group at the beginning of the run (when the PFP group had no pain). The authors of this study hypothesized that injured runners who experience pain after an exhaustive run may not be flexible enough to respond to the internal and external perturbations compared to the healthy group.

One possible reason for the inconsistent findings of the above-mentioned studies may be due to the different methods used to calculate the coordination variability. According to a study by Miller et al. [38], which compared two methods of CRP and Vector Coding for calculating coordination variability, although both methods are valid for measuring coordination variability from the perspective of dynamic systems, these two methods do not always tell the same story, especially if variability is measured at certain times or parts of a movement cycle. CRP was introduced as a more conservative method than Vector Coding. They suggested that comparisons between the findings of studies that have quantified variability using CRP and those that have used vector coding should be made with caution.

It also seems that the type of couplings examined in each study is one of the factors that can affect the results and therefore should be considered in comparing the results of the studies, especially whether these couplings are between segments or between joints.

Another noteworthy point is the parts of the walking or running cycle that are selected for analysis. In the above studies, significant differences in variability of the evaluated couplings between study groups occurred in different parts of running cycles (the whole cycle, stance phase, swing phase, different intervals of stance phase), which may be one of the sources of the discrepancy between the findings.

In the present study, the effect of increasing task demand (mainly due to increasing speed) on coordination variability was also evaluated. Apart from the couplings in which both groups responded similarly to the increasing task demand, there were some couplings in which the PFP, not the control group showed significant between-trial differences. Based on the results, the PFP group showed significant reduction in coordination variability of Ths-Sht, Sht-Ft, and Shs-Ft during stance by increasing task demand from walking to each of the running trials and also from preferred speed to fixed speed running. They also showed significant reduction in coordination variability of Thf-Sht and Sht-Fs during stance from walking to each of the running trials.

Amplitude-centered Hilbert transform adopted in the present study to calculate the CRP, has been suggested to remove frequency artifacts of the non-sinusoidal signals [22] and also to rectify the order error (changes in the order of coordination from proximal-distal to distal-proximal and vice versa); so it is proposed that the Hilbert transform is superior to the conventional method (constructing the phase-plane portrait by plotting velocity over position) for calculating CRP in human movement data [39].

The present study had some limitations that should be acknowledged: 1) The cross-sectional design of the present study does not allow us to examine the cause-and-effect relationship between PFP and coordination variability. Future prospective studies are needed to find this relationship. 2)

All participants wore standard shoes to minimize the confounding factors related to the footwear which might affect the variability of segmental couplings in participants who were not accustomed to the standard shoes. 3) The participants all were women in the age range of 18 to 35 years, so our findings cannot be generalized to men or women with different levels of activity and age groups.

5 Conclusion

In summary, people with PFP exhibited less coordination variability of lower limb intersegmental couplings assessed by CRP compared to the healthy group. Reduced coordination variability can reduce the system flexibility to adapt to local and environmental perturbations and may cause progressive wear and tear of articular tissues by reducing the available movement patterns for performing the desired task. Moreover, it can also be concluded that the differences in intersegmental coordination variability between PFP and healthy groups would be exacerbated by increasing task demand.

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Compliance with Ethical Standards

Conflict of interest The authors declare no conflict of interest.

Ethical Approval Ethical approval was granted by the local Ethics Committee of Shiraz University of Medical Sciences (IR.SUMS.REHAB.REC.1397.006).

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