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ORIGINAL ARTICLE

Coordination Variability During Walking and Running in Individuals With and Without Patellofemoral Pain Part 2: Proximal Segments Coordination Variability

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Abstract

Purpose There is a scarcity of studies evaluating the variability of couplings between proximal segments (trunk, pelvis, and thigh) in individuals with patellofemoral pain (PFP) while emerging evidence has suggested that aberrant motions of trunk and pelvis can have a contributory role in the etiology of PFP. The purpose of this study was, therefore, to evaluate the trunk, pelvis, and thigh intersegmental coordination variability in PFP compared with healthy individuals.

Methods Thirty-four participants (17 with PFP and 17 healthy controls) walked (at preferred speed) and ran (at preferred and fixed speed) on a treadmill each trial for 30 seconds. Three-dimensional kinematics were recorded using a motion capture system. Continuous Relative Phase was used to calculate the coordination variability of couplings between trunk, pelvis, and thigh.

Results The PFP group was significantly less variable at trunk-thigh and pelvis-thigh in frontal plane during stance at preferred speed running and trunk-pelvis in sagittal plane during swing irrespective of trial. The variability differences of the following couplings among study groups tended to be significant with the PFP group showing lesser values: trunk-thigh and pelvis-thigh in frontal plane during stance at fixed speed running, trunk-pelvis in frontal plane during swing at preferred speed running and trunk-thigh in sagittal plane during swing.

Conclusion Lower variability in coordination of trunk, pelvis, and thigh in individuals with PFP indicates the system's reduced ability to transit between movement patterns and to respond to different perturbations which could result in the progression of the patellofemoral joint injury.

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

1 Introduction

Although the underlying etiologic factors of patellofemoral pain (PFP) are not exactly understood, the most common probable hypothesis is elevated patellofemoral (PF) joint loading resulting from patellar malalignment or maltracking [1]. In addition to the abnormal lower extremity kinematics which has been recognized to affect the PF joint mechanic, emerging evidence has suggested that aberrant motions of the trunk and pelvis especially in frontal and sagittal planes can also affect the PF joint function [2–4]. It is theorized that pelvic instability in the frontal (resulted from weak hip abductor muscles) and sagittal (resulted from weak hip extensor muscles) planes induce trunk compensatory movements to lessen the demand on weak muscles which in turn influence the position of the resultant ground reaction force (GRF) vector and moments on the knee joint [2].

As with the studies investigating lower extremity joints and segments kinematic in individuals with PFP, biomechanical studies evaluating trunk and pelvis kinematics in this population yielded inconsistent results [3–7]. It is taught

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that one of the reasons for the lack of agreement in the abovementioned studies could be that these studies assess kinematic variables of discrete joints or segments at discrete time points while human functional movements require coordination of multiple degrees of freedom (DoF) (joints, segments and etc.) over a period of time [8]. So, a macroscopic analysis method considering the coordination of interacting DoF seems necessary to better capture the human movement and give a clearer picture of the etiology of injuries.

A large number of DoF in the human body, enrich the system with different solutions (coordinative structures) to achieve a goal [9]. Hence, the variability in movement patterns is considered functional as it makes the system flexible to select the proper movement pattern in response to any internal and external perturbations [8, 10]. Based on the dynamic system theory (DST) perspective to musculoskeletal overuse injuries, the intersegmental coordination variability decreases with pathology, and using highly repeatable and predictable movement patterns over time results in continuous stress to the same tissues and therefore, overuse injury [11, 12]. The first application of DST for investigating the orthopedic injuries was the study by Hamill et al. [13] who reported lower variability in couplings between lower limb segments in PFP compared with the control group. They concluded that patients with knee pain constrained the available movement patterns to avoid painful ones. Since then, a few numbers of studies have been conducted to investigate the intersegmental or inter-joint coordination variability in PFP compared with control group and inconsistent findings were reported [8, 14–16]. Using modified vector coding (a spatial coordination measure based on the angle-angle plot), Heidersheit et al. [15] reported less coupling angle variability (CAV) while Cunningham et al. [14] and Jewell et al. [16] reported more CAV during running in PFP compared with the control group. In part 1 of the present study [17], the lower limb intersegmental coordination variability of patients with PFP was assessed using the continuous relative phase (CRP) method, and significantly lesser CRP variability was observed in a variety of assessed couplings in PFP compared with the healthy controls.

Despite close interaction between the kinematics and function of core segments (e.g. trunk and pelvis) and PF joint [2, 18], to the best of the author's knowledge, only one recent study evaluated the variability of intersegmental couplings which contain a core segment. Jewell et al. [16] investigated the effect of PFP on intersegmental coordination variability over a prolonged treadmill running using modified vector coding technique. The two couplings containing pelvis segment were pelvis frontal-thigh frontal and pelvis frontal-thigh transverse. No between-group differences were found in the coordination variability of these two couplings. The runners with PFP showed a decrease in coordination variability of pelvis frontal-thigh frontal as the pain increased at the end of the prolonged run compared to the beginning.

Owing to the scarcity of studies investigating coordination variability between core and lower limb segments in individuals with PFP, and to better understand how chronic PFP influence the trunk, pelvis and thigh intersegmental coordination variability, the purpose of the present study was to evaluate the coordination variability of multiple intersegmental couplings containing trunk and or pelvis using CRP during walking and running. Based on the study by Hamill et al. [13], it was hypothesized that females with PFP would show less CRP variability compared with healthy controls. It was also hypothesized that these group differences would be aggravated by increasing task demand.

2 Methods

2.1 Participants

Thirty-four females aged 18–35 years (17 individuals with unilateral PFP and 17 healthy controls) were recruited after signing a written consent form. Ethical approval for this study was obtained from the local Ethics Committee of Shiraz University of Medical Sciences (IR.SUMS.REHAB.REC.1397.006). PFP and control group's inclusion and exclusion criteria are listed in Table 1.

2.2 Data Acquisition

Kinematic data during preferred speed walking (PSW), preferred speed running (PSR), and fixed speed running (FSR) on a treadmill (PROTEUS IMT-8000/8500, Philippines) were collected using an eight-camera, 3-dimensional motion analysis system (Proreflex, Qualisys Medical AB, Gothenburg, Sweden) at a sampling rate of 200 Hz. Retro-reflective markers were positioned on the subjects anatomical landmarks to model the trunk, pelvis, and thigh segments: Both acromion processes, spinous process of C7, T7, T10, and T12 vertebrae, upper and lower back, the xiphoid process of sternum, highest points of iliac crests, anterior superior iliac spines, posterior superior iliac spines, the center of the greater trochanter, medial and lateral femoral condyles. A rigid body cluster consisting of 4 markers was wrapped at lateral-distal aspects of the thigh using an elastic strap. A reflective marker was also placed on the shoe at the heel to detect gait events through the vertical displacement algorithm [19]. All participants wore the same brand of standard shoes to minimize the confounding factors related to footwear. To determine the preferred speeds of walking and running, 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 reported a comfortable speed. The participants were blinded to treadmill speed

Table 1 Inclusion and exclusion criteria for PFP and control groups

Study group	Inclusion criteria	Exclusion criteria
PFP	Insidious onset of peri- or retropatellar pain lasted for at least 3 months	Other knee injuries except for PFP such as ligamentous instability, meniscal pathology, plica syndrome, osteoarthritis, patellar subluxation or dislocation, bursitis, patellar tendonitis, etc.,
	Pain provoked by at least 2 of the following activities: running, stair ambulation, prolonged sitting, kneeling, squatting, jumping and hopping	Visible lower extremity structural malalignment or other orthopedic conditions which could affect the gait
	Pain evoked by palpation of medial and/or lateral patellar facets, quadriceps isometric contraction or applying a compressive force on the patella	History of any lower limb inflammatory process or metabolic disease like diabetes
	Pain intensity of at least 3 in11-point NRS (0–10)	History of cardiovascular pathologies
	Positive patellar apprehension test	Neurological disease
		Pregnancy
	Score less than 85/100 on the KAPS	Have received physiotherapy, opiate treatment, acupuncture or oral steroids within past 6 months
		Professional athletes
Control	Age, height, mass and the evaluated limb side matched to the PFP group	Same as PFP group

PFP patellofemoral pain, *NRS* numerical rating scale, *KAPS* kujala anterior knee pain scale

display. To assess the possible confounding effects of different preferred speeds, the speed of 2.68 m/s was set as the 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].

After getting familiarized with treadmill walking and running, the participants performed a static standing calibration trial, and marker positions were collected for 3 s. Following that, dynamic trials, each for 30 s with enough rest in between were performed and 3-dimensional marker trajectories were recorded.

2.3 Data Analysis

Retroreflective markers were identified and labeled through Qualisys Track Manager software. Then marker trajectories were exported to Visual3D software (C-Motion®, Rockville, MD, USA) to extract 3-dimensional segment angles of trunk, pelvis, and thigh. Kinematic data were low-pass filtered using a fourth-order Butterworth filter with a cut-off frequency of 9 Hz. Three-dimensional segment angles were defined relative to the global coordinate system using Cardan rotation sequences of X–Y–Z. CRP is a new signal calculated by the difference between phase angles of the original signals of two related segments. First, segment kinematics were interpolated to 100% of a gait cycle, and the range of the signal's amplitude was centered around zero [21]. Then, the phase angle for time series ($X(t)$) of each segment was calculated using Hilbert transform. The Hilbert transform creates a complex, analytic signal ($\zeta(t)$) from the real signal itself ($X(t)$) and its Hilbert transform ($H(t)$).

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

The phase angle at time t then was calculated as

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

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

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

where the $H_1(t)$ and $H_2(t)$ indicate the Hilbert transform of $X_1(t)$ and $X_2(t)$, respectively.

Then, the mean ensemble average curves for each intersegmental couple in each dynamic trial were averaged across all gait cycles. Finally, the standard deviation of the ensembled CRP curve points was averaged to calculate the deviation phase (DP) as the coordination variability.

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

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 denote less coordination variability and vice versa.

The intersegmental couplings of interest extracted during both stance and swing phase are listed in Table 2.

Table 2 Intersegmental couplings and their abbreviated forms

Intersegmental coupling	Abbreviations
Trunk $_{sagittal}$-Pelvis $_{sagittal}$	Trs-Ps
Trunk $_{frontal}$-Pelvis $_{frontal}$	Trf-Pf
Trunk $_{sagittal}$-Thigh $_{sagittal}$	Trs-Ts
Trunk $_{frontal}$-Thigh $_{frontal}$	Trf-Tf
Pelvis $_{sagittal}$-Thigh $_{sagittal}$	Ps-Ts
Pelvis $_{frontal}$-Thigh $_{frontal}$	Pf-Tf

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 PSW, 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 $P \leq 0.05$.

3 Results

Both PFP and control groups were similar in terms of age, height, weight, and preferred speed of walking and running (Table 3). PFP group tended to run with lower speed at PSR compared with the control group ($P = 0.057$).

Tables 4 and 5 summarizes the repeated measure ANOVA results for CRP variability of interest couplings. There was significant group by trial interactions ($P < 0.05$) for CRP variability of Pf-Tf during stance (Table 4) and Trf-Pf during swing (Table 5). Significant interaction effects and the interaction tended to be significant (Trf-Tf, stance, $P = 0.074$) (Fig. 1) were broken down to compare the relevant variables between two groups in each trial and also between 3 trials in each group: Significant group differences were found for Trf-Tf ($P = 0.012$) and Pf-Tf ($P = 0.014$) during

Table 3 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 4 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)*
Trs-Ps	Control	36.10 ± 7.53	32.71 ± 9.20	30.82 ± 7.80	0.45 (0.638)	2.00 (0.166)	3.45 (0.044*)
	PFP	34.34 ± 7.33	28.59 ± 6.93	28.38 ± 9.99			
Trf-Pf	Control	29.57 ± 8.24	22.64 ± 4.22	23.17 ± 5.31	0.07 (0.928)	0.70 (0.409)	12.43 (< 0.001*)
	PFP	27.57 ± 9.30	21.39 ± 7.52	21.40 ± 8.73			
Trs-Ts	Control	24.52 ± 10.02	28.08 ± 11.80	27.05 ± 10.89	0.42 (0.660)	1.97 (0.170)	1.01 (0.374)
	PFP	23.38 ± 6.49	24.06 ± 6.79	22.39 ± 7.55			
Trf-Tf	Control	29.53 ± 8.65	31.51 ± 8.82	29.48 ± 7.04	2.83 (0.074)	3.56 (0.068)	0.89 (0.419)
	PFP	30.01 ± 10.28	23.90 ± 7.76	24.21 ± 9.63			
Ps-Ts	Control	32.02 ± 10.67	19.09 ± 8.92	20.79 ± 8.79	0.30 (0.740)	0.07 (0.787)	17.79 (< 0.001*)
	PFP	32.02 ± 10.67	19.57 ± 8.17	20.90 ± 11.14			
Pf-Tf	Control	19.65 ± 5.32	26.19 ± 10.68	23.50 ± 7.48	4.57 (0.018*)	3.69 (0.064)	1.14 (0.332)
	PFP	21.61 ± 4.35	18.42 ± 5.68	18.76 ± 6.55			

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

*$P < 0.05$

Table 5 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)*
Trs-Ps	Control	35.47 ± 11.52	33.84 ± 6.54	34.92 ± 7.64	0.07 (0.929)	7.23 (0.011*)	0.51 (0.604)
	PFP	29.54 ± 10.38	29.04 ± 7.39	29.61 ± 6.89			
Trf-Pf	Control	24.67 ± 13.05	24.78 ± 6.91	25.05 ± 7.49	3.29 (0.050*)	0.006 (0.938)	3.81 (0.033*)
	PFP	30.65 ± 15.46	20.74 ± 5.78	22.54 ± 5.97			
Trs-Ts	Control	18.35 ± 11.99	31.85 ± 8.84	32.02 ± 11.55	0.46 (0.635)	4.04 (0.053)	24.63 (< 0.001*)
	PFP	30.00 ± 10.28	23.89 ± 7.76	24.21 ± 9.63			
Trf-Tf	Control	29.22 ± 12.68	24.26 ± 5.72	24.54 ± 6.23	1.56 (0.225)	0.65 (0.424)	7.53 (0.002*)
	PFP	35.72 ± 10.55	24.24 ± 8.67	23.37 ± 7.05			
Ps-Ts	Control	30.60 ± 11.50	19.92 ± 9.14	20.97 ± 9.51	0.79 (0.461)	0.76 (0.388)	14.22 (< 0.001*)
	PFP	25.44 ± 9.36	19.23 ± 4.72	20.48 ± 6.96			
Pf-Tf	Control	23.13 ± 9.26	20.73 ± 4.96	21.75 ± 5.82	0.83 (0.443)	0.43 (0.515)	3.78 (0.034*)
	PFP	27.84 ± 10.87	20.38 ± 9.13	21.58 ± 7.83			

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

*$P < 0.05$

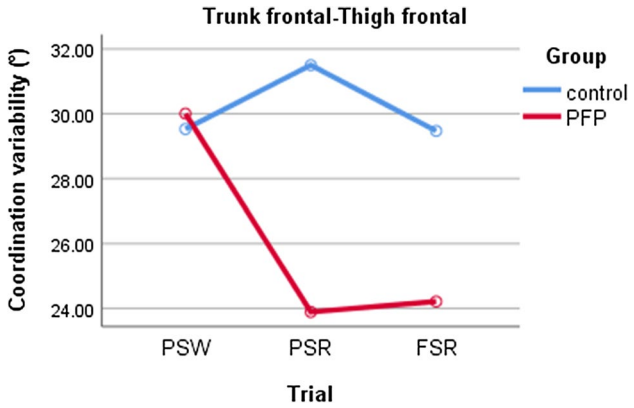

Fig. 1 Line graph showing the significant group by trial interaction for coordination variability of trunk frontal-thigh frontal during stance; *PFP* patellofemoral pain, *PSW* preferred speed walking, *PSR* preferred speed running, *FSR* fixed speed running

stance at PSR with PFP group demonstrating significantly less coordination variability. The PFP group also tended to be less variable in Trf-Tf (P = 0.078), Pf-Tf (P = 0.058) during stance at FSR and Trf-Pf (P = 0.074) during swing at PSR compared with the control group (Fig. 2). Pairwise comparisons between trials in each group showed no significant differences and only the coordination variability of Trf-Pf during swing tended to be lower at PSR compared with PSW (Fig. 2).

Significant main effect for group was found for CRP variability of Trs-Ps during swing, with PFP group demonstrating less coordination variability compared with the control group (Table 5). The main effect for group tended to be significant for CRP variability of Trs-Ts during swing, with the PFP group showing less variability compared with the control group (Table 5).

Significant main effects for trial were found for Trs-Ps, Trf-Pf, Ps-Ts during stance (Table 4) and for Trf-Pf, Trs-Ts, Trf-Tf, Ps-Ts, and Pf-Tf during swing (Table 5). Coordination variability of Trs-Ps, Trf-Pf, Ps-Ts during stance (Table 4) and Trf-Pf, Trf-Tf, Ps-Ts, Pf-Tf during swing (Table 5) was lower at FSR and PSR compared with PSW. Coordination variability of Trs-Ts during swing was higher at FSR and PSR compared with PSW.

4 Discussion

In the present study, trunk, pelvis, and thigh intersegmental coordination variability in individuals with PFP differed significantly from healthy controls during treadmill running. The PFP group was significantly less variable at Trf-Tf and Pf-Tf during stance at PSR and Trs-Ps during swing regardless of trial. The variability differences of the following couplings among study groups tended to be significant with the PFP group showing less values: Trf-Tf and Pf-Tf during stance at FSR, Trf-Pf during swing at PSR and Trs-Ts during swing regardless of trial.

The rationale for selecting the assessed intersegmental couplings was based on the normal motions of trunk, pelvis, and thigh segments during walking and running and their kinematic alterations in patients with PFP. During running, from beginning to the end of the stance phase, the range of trunk forward flexion, pelvic anterior tilt, and hip extension

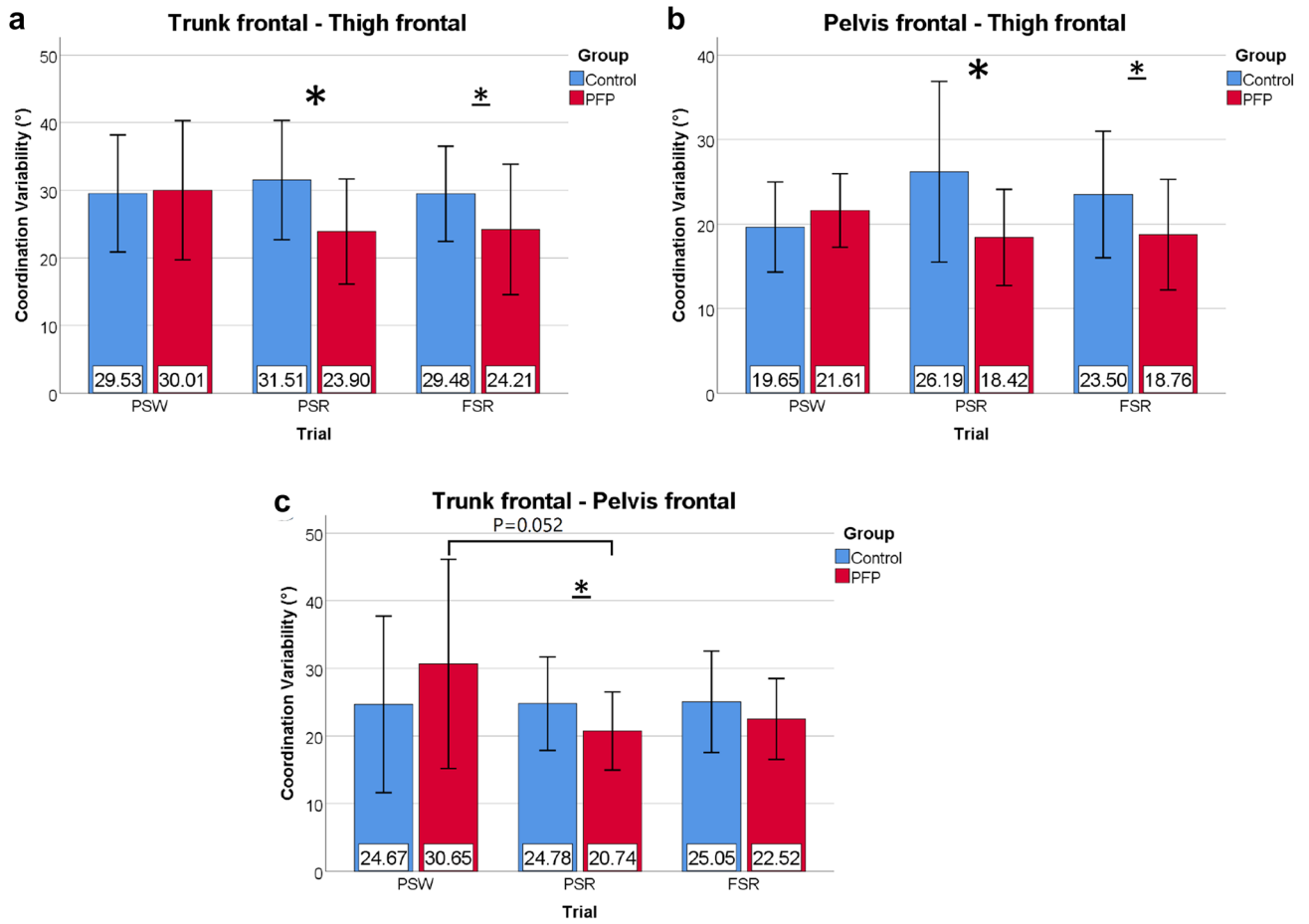

Fig. 2 Bar graphs illustrating the significant interaction between group (control and patellofemoral pain (PFP)) and gait trial (preferred speed walking (PSW), preferred speed running (PSR) and fixed speed running (FSR)) for intersegmental coordination variability. **a** Trunk frontal-Thigh frontal during stance, **b** Pelvis frontal-thigh frontal during stance, **c** Trunk frontal-pelvis frontal during swing. 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 difference, *group differences tended to be significant

constantly increase and during the swing phase, these events reverse. In the frontal plane, at heel strike and during the initial stance phase, lateral trunk bending and lateral pelvic tilt occur toward and away from the stance limb while the hip joint adduction increases. After the initial stance and until the initial swing, these events reverse, and during the remainder of the swing phase, the second reversal of motions occurs. In the transverse plane, there are opposite direction movements of pelvis and hip joint, so that during the first half of the stance phase, pelvic external rotation and hip joint internal rotation occur simultaneously and during the second half of the stance phase, these events reverse and until the end of the first half of the swing phase they constantly increase. During the second half of the swing phase, the second reversal of motions occurs. The pattern of trunk, pelvis and thigh movements during walking is very similar to their pattern during running except for the transverse plane movements which are opposite to each other [22]. It should be noted that all mentioned movements are coupled with each other and interrelated [22]. It has been reported that individuals with PFP show trunk, pelvis, and hip joint (thigh relative to pelvis) kinematic differences compared with healthy individuals, but findings across studies are inconsistent [3–7]. As mentioned during normal running, the movements of trunk, pelvis, and thigh segments are coupled, while the kinematic studies focus on evaluating individual joints and segments at discrete time points and this is proposed as the main source for the inconsistent results these studies provided. Based on the results of the present study, the analysis of intersegmental coordination variability which considers the relationship between segments and joints during running could discriminate between individuals with PFP and healthy controls. Lower intersegmental coordination variability in individuals with PFP compared

with the healthy individuals in the present study is consistent with DST, suggesting that with injury, the number of intersegmental couplings was used to accomplish the desired task and therefore the coordination variability is reduced; so the system is no longer as flexible to use the proper coordinative structure in order to adapt the perturbations and instead shows highly repeatable movement patterns [11, 12]. Using highly repeatable movement patterns combined with reduced patellofemoral joint contact area resulting from aberrant motions of trunk and pelvis or abnormal kinematic of thigh relative to the pelvis may accelerate the onset and progression of articular cartilage wear and therefore PFP. Although the assessed couplings were different, it can be said that the results of the present study are consistent with those of Hamill et al. [13], Heiderscheit et al. [15], and also the first part of the present study [17] suggesting that lower amount of coordination variability is characteristic of patients with PFP. In these studies, the lower limb intersegmental coordination variability was compared between PFP and healthy individuals. In the study by Hamill et al. [13], it was assumed that reduced coordination variability in the PFP group is because the symptomatic subjects try to avoid using the painful patterns, so they can continue and accomplish the running task without pain; however, it does not seem a suitable long term solution because employing the same pattern repeatedly induce overuse injury in the related soft tissues which eventually leads to pain and dysfunction.

Using modified vector coding, Heiderscheit et al. [15] found a significant reduction in coupling angle variability of thigh rotation-leg rotation in the PFP compared with the control group at PSR near the heel strike. No differences were observed between groups during the rest of the cycle or for the other couplings. The other couplings assessed in the study by Heiderscheit were between joints not segments while in the present study all assessed couplings were intersegmental.

However, the results of the present study do not confirm those of Cunningham et al. [14] and Jewel et al. [16]. The former found that patients with PFP exhibited higher variability at hip-knee couplings compared with healthy subjects after 11 min treadmill running and the latter found the PFP not the healthy individuals showed lower CAV of pelvis frontal-thigh frontal after 21 min treadmill running when they experienced pain compared with the beginning of the run. They also found higher CAV of thigh sagittal-shank sagittal in patients with PFP at the beginning of running compared with the healthy individuals which is contrary to the DST perspective to overuse injury and the hypothesis proposed by Hamill et al. [13]. Both studies used modified vector coding to quantify the coupling angle variability.

One possible reason for the controversy between the findings of the above studies could be due to the different methods they used to quantify the coordination variability. According to Miller et al. [23] who compared the two methods of CRP and Vector Coding for calculating coordination variability, these two methods do not always tell the same story although both methods are valid criteria to measure coordination variability. CRP seemed a more conservative method than Vector Coding, so the comparison between studies that used CRP with those that used vector coding to calculate the coordination variability needs caution. Moreover, the level of fatigue, the duration of running, the type of assessed couplings, and the cycle interval at which assessments have been done, all seem important factors that potentially affect the coordination variability and should be considered. Another explanation for these conflicting results may be this perspective that healthy states are associated with an optimal amount of variability and extreme amounts of variability (greater or lesser than optimal) are detrimental to the biological system and characterize systems that are less adaptable to different perturbations [24].

In contrast to the first part of the present study [17], increasing task demand (mainly due to increasing speed) did not exacerbate the difference between PFP and healthy groups meaning both groups responded similarly to increasing the task demand from preferred walking to preferred and fixed running regarding proximal segments coordination variability.

In the first part of this study, it was observed that almost all between-group differences in lower limb intersegmental coordination variability occurred in the stance phase [17], while in the present part of the study, between-group differences occurred in both the stance and swing phases, with frontal plane couplings showing significant between-group differences during the stance and sagittal plane couplings showing significant between-group differences during the swing phase. As mentioned before and based on the previous studies, individuals with PFP have weak hip abductors that induce contralateral pelvic drop and trunk compensatory movement while the affected limb is in the stance phase which eventually results in changed resultant GRF vector in relation to the knee joint, knee joint malalignment, reduced PF joint contact area and increased joint pressure and pain [2]. It seems that reduced coordination variability of Trf-Tf and Pf-Tf in stance phase of running is a protective strategy aimed at avoiding movement patterns exacerbating pain. Moreover, it is reported that individuals with PFP tend to increase the anterior pelvic tilt due to hip extensor weakness which results in trunk compensatory extension [2]. In addition, the amount of trunk extension and pelvic posterior tilt increase during the swing phase of normal walking and running [22]. Increased trunk extension can cause the resultant GRF to fall behind the knee which increases the demand on knee extensors and as a result the PF joint pressure. Decreased trunk-pelvis and trunk-thigh coordination variability in sagittal plane during swing again seems

a protective strategy aimed at limiting the use of painful patterns.

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 [21] 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 [25].

The present study had some limitations that should be noted: The cause-effect relationship between PFP and reduced coordination variability could not be examined in this study due to its cross-sectional design and future prospective studies are needed to find this relationship. Using the same standard shoes for all participants aimed at minimizing the confounding factors related to the footwear, might affect the variability of segmental couplings especially in participants who were not accustomed to the shoes. Since the participants in this study were women aged 18 to 35 years, so the findings cannot be generalized to men or women with different age or activity level.

5 Conclusion

According to the results, individuals with PFP showed less coordination variability for couplings between proximal core segments including trunk, pelvis, and thigh during walking and running compared with their healthy counterparts. Lesser coordination variability and therefore inability to adapt to internal and environmental perturbations could expose them to risk of injury progression which could lead to degenerative changes of patellofemoral articular surface and osteoarthritis. The findings of both parts of this study highlighted the importance of examining the intersegmental coordination variability, not only for couplings between lower limb segments but also the couplings including proximal segments (such as trunk and pelvis), as order parameters to evaluate the patients with PFP and to assess the effectiveness of different therapeutic modalities while considering control parameters such as speed. Facilitating the coordination variability in clinical treatments may improve gait performance in individuals with PFP.

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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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