Gait & Posture 89 (2021) 80–85

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Trunk, pelvis, and knee kinematics during running in females with and without patellofemoral pain

Farzaneh Haghighat [a], Samaneh Ebrahimi [b,c], Mohammadreza Rezaie [c], Ehsan Shafiee [c], Seyed Mohammadreza Shokouhyan [d], Alireza Motealleh [b,c,*], Mohamad Parnianpour [d]

[a] Student Research Committee, Shiraz University of Medical Sciences, Shiraz, Iran
[b] Physical Therapy Department, School of Rehabilitation Sciences, Shiraz University of Medical Sciences, Shiraz, Iran
[c] Rehabilitation Sciences Research Center, Shiraz University of Medical Sciences, Shiraz, Iran
[d] Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran

ARTICLE INFO

Keywords:
Patellofemoral pain syndrome
Anterior knee pain
Patellofemoral joint
Biomechanics
Motion analysis
Patella

ABSTRACT

Background: Females are two times more likely to develop patellofemoral pain (PFP) than males. Abnormal trunk and pelvis kinematics are thought to contribute to the pathomechanics of this condition. However, there is a scarcity of evidence investigating proximal segments kinematics in females with PFP.
Research question: The purpose of this study was to investigate whether females with PFP demonstrate altered trunk, pelvis, and knee joint kinematics compared with healthy controls during running.
Methods: Thirty-four females (17 PFP, 17 controls) underwent a 3-dimensional motion analysis during treadmill running at preferred and fixed speeds, each trial for 30 s. Variables of interest included magnitudes of peak angles for trunk (forward flexion, ipsilateral trunk lean), pelvis (anterior tilt, contralateral drop), knee (flexion, valgus, internal rotation), range of motion (RoM) of trunk and pelvis in sagittal and frontal planes and RoM of knee joint in the three cardinal planes of motion. Kinematic data were compared between groups using mixed model repeated measure analysis of variance with the trial as the repeated measure.
Results: The PFP group displayed significantly less pelvis frontal plane RoM, greater knee frontal plane RoM, and less knee sagittal plane RoM during running compared with controls, irrespective of running trial. No differences were found in peak kinematic variables between PFP and healthy groups.
Significance: These results may suggest a rigid stabilization strategy at the pelvis, which the body has adapted to prevent further frontal plane knee malalignment. Less knee sagittal plane RoM may be indicative of another protective strategy in the PFP group to avoid patellofemoral joint reaction force. Clinical assessments and rehabilitative treatments may benefit from considering a global program with focus on pelvis kinematics in addition to the knee joint in females with PFP.

1. Introduction

Patellofemoral pain (PFP) is often considered as the most common overuse injury of the lower extremity [1]. It is characterized by diffused peri- or retropatellar pain aggravated by activities that increase joint loading [2]. Annually, 29 % of adolescents and 23 % of adults report PFP in the general population [3]. Females are reported to be two times more likely to develop PFP compared with males [3]. The high recurrence rate of 70%–90% has made this condition an enigma for clinicians [1,4]. This condition may predispose the individual to develop patellofemoral (PF) osteoarthritis later in life [5]. While short-term outcomes of PFP treatments may be positive, long-term results are disappointing [6,7].

Although the exact etiology of PFP is still not well-understood, it has been commonly assumed that abnormal loading of PF joint and elevated joint stress underlie the development of PFP [8]. It has been suggested that PF contact pressure may be influenced by several kinematic factors during gait. Excessive dynamic knee valgus resulting from tibial abduction (relative to the femur), femoral adduction (relative to the pelvis), or the combination of both, is believed to increase PF joint contact pressure by inducing lateral patellar tracking and decreasing the PF contact area [9,10]. Moreover, greater knee flexion increases PF compressive loads and it has been suggested that decreasing knee flexion

* Corresponding author at: School of Rehabilitation Sciences, 1 Abiverdi St., Chamran Blvd, Shiraz, Iran.
E-mail address: motealleh@sums.ac.ir (A. Motealleh).

https://doi.org/10.1016/j.gaitpost.2021.06.023
Received 22 October 2020; Received in revised form 24 June 2021; Accepted 26 June 2021
Available online 29 June 2021
0966-6362/

is a protective or compensatory strategy to reduce joint loading [11,12]. Findings of knee joint kinematic differences in participants with PFP compared with injury-free individuals during running are inconsistent across studies [13–17]. Although less peak knee flexion [14] and greater peak knee valgus [13] have been reported in those with PFP compared with healthy participants, others have found no differences in peak knee flexion [13,16,17] or knee valgus [14–16,18,19] between these groups. Similarly, transverse plane knee rotation is not consistent across studies; while increased knee internal rotation has been reported in PFP compared with the healthy controls [15,17], other studies have shown that peak knee internal rotation in those with PFP is less than [16] or not different [13,14] from healthy participants. These divergent and inconsistent results may be attributed to various confounding methodological factors such as the time interval of the stance phase at which the discrete values were selected, differences in participant's inclusion criteria, sex of participants, and the duration of the PFP. However, it is proposed that suboptimal lower limb kinematics coupled with repeated loading cycles during running, damage the retropatellar cartilage and induce pain and symptoms related to PFP [20].

The PF joint has also been reported to be influenced proximally by aberrant motions of the trunk and pelvis in frontal and sagittal planes [10,13,21]. In the presence of hip abductor weakness, which is commonly reported in individuals with PFP [22], the pelvis may drop on the contralateral side of the stance limb [10]. It has been theorized that individuals with PFP compensate for the weakness of hip abductor muscles by leaning the trunk toward the stance limb and elevating the contralateral pelvis [10,14].

Considerable debate exists regarding the trunk and pelvis kinematics during running in participants with PFP. In the study by Bazett-Jones et al. [13], the fatigue effect of an exhaustive run was assessed on the trunk and pelvis kinematics in individuals with and without PFP, and no difference between groups at the beginning and end of the prolonged run was reported. In the study by Noehren et al. [18], a trend toward reduced contralateral trunk lean was found in female runners with PFP. In contrast to Willy et al. [23] and Willson et al. [16], who reported a significantly greater contralateral pelvic drop in patients with PFP compared with healthy controls during running, Esculier et al. [24] and Noehren et al. [18] found no difference in contralateral pelvic drop between these groups.

Owing to the paucity of research investigating the trunk and pelvis kinematics during running in individuals with PFP, as well as the suggested contributory role of the aberrant trunk and pelvis motion in malalignments of the knee and therefore the PF joint, the purpose of this study was to compare trunk, pelvis, and knee joint kinematics in females with and without PFP during running at the preferred and fixed speeds. It was hypothesized that females with PFP would demonstrate greater peak ipsilateral trunk lean, forward trunk flexion, contralateral pelvic drop, anterior pelvic tilt, knee flexion, knee valgus, knee internal rotation during preferred and fixed speed running compared with the control participants.

2. Methods

2.1. Participants

Thirty-four females aged 18–35 years participated in a cross-sectional study: 17 healthy controls (24.12 ± 3.90 years, 56.38 ± 5.70 Kg, and 1.61 ± 0.06 m) and 17 individuals diagnosed with unilateral PFP (25.94 ± 3.99 years, 59.70 ± 10.82 Kg and 1.63 ± 0.05 m). They were recruited from the general population (not professional or recreational runners) *via* advertisements placed in Shiraz University of Medical Sciences and the surrounding community. The sample size was calculated based on the peak lateral trunk lean variable from the previous study [18] using G*power software (version 3.1). Considering an effect size of 0.57, power of 80 %, and a significance level of 0.05, 17 participants in each group were required for adequate statistical power. All participants signed a written informed consent before their participation and the study procedure was approved by the local Ethics Committee of Shiraz University of Medical Sciences. All participants ran with an observed heel-strike pattern. Each participant was initially screened by an experienced physical therapist to ensure they met the inclusion and exclusion criteria. PFP group inclusion criteria were: 1) insidious onset of peri- or retropatellar pain persisted for at least three months [25], 2) pain provoked by at least 2 of the following activities: stair ambulation, squatting, running, kneeling, prolonged sitting, jumping and hopping, 3) pain elicited by palpation of medial and/or lateral patellar facets, isometric contraction quadriceps muscle or PF joint compression force, 4) average pain intensity of at least 3 in 0 (no pain) to 10 (maximum pain) point numerical rating scale (NRS) in the previous week, 5) positive clinical sign at patellar apprehension test (sensitivity: 86.7 %, specificity: 86.7 %) [26], 6) score less than 85/100 on the Kujala anterior knee pain scale [27]. Exclusion criteria for the PFP group were as follows: 1) any other knee injury or pathology, such as patellar tendonitis, ligamentous instability, meniscal pathology, knee joint internal derangement, plica syndrome, osteoarthritis, bursitis, patellar subluxation or dislocation, etc., 2) Any visible lower extremity structural malalignment or other orthopedic conditions like leg length discrepancy which could affect the gait, 3) history of any inflammatory process of the lower limbs or metabolic disease like diabetes, 4) history of cardiovascular pathologies, 5) neurological disease, 6) pregnancy, 7) receiving physiotherapy, opiate treatment, acupuncture, oral steroids or have received them within past six months, 8) professional athletes including runners. The healthy individuals served as the control group and were matched to the PFP group based on age, height, mass and the assessed limb side. They did not have any history of lower extremity injury or knee pain. The other exclusion criteria of the control group were the same as the PFP group.

2.2. Data acquisition

Kinematic data during running was collected using an eight-camera, 3-dimensional motion analysis system (Proreflex, Qualisys Medical AB, Gothenburg, Sweden) at a sampling rate of 200 Hz. Running trials were conducted on a treadmill (PROTEUS IMT-8000/8500, Philippines) with zero inclination. Based on the calibrated anatomical systems technique (CAST) using a 6 degrees of freedom (DOF) model [28], retro-reflective markers were attached to the participant's specific anatomical landmarks by the same investigator to model the trunk, pelvis, and knee articulation: acromion, 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, medial and lateral malleoli. Moreover, rigid body clusters containing four markers were wrapped at distal aspects of thigh and shank, using elastic straps. A reflective marker was placed on the shoe at the heel to detect heel contact and toe-off events, using the vertical displacement algorithm [29]. It should be noted that to minimize the confounding factors relating to footwear, all participants wore standard shoes with the same brand and material (WORLDCUP, minimal heel-to-toe drop, made in Korea).

Upon completion of the marker placement, a 3-second standing static trial was captured while the participants stood on the treadmill to establish a baseline orientation for the dynamic trials. Next, participants underwent a 7-minute warm up session on the treadmill which consisted of walking and running. The participant's preferred speed of running was determined during the warm up. They also experienced running at fixed speed in the meanwhile. In order to determine the preferred speed of running, while participants were blinded to treadmill speed, the investigator increased or decreased speed between the range of 2.2–3.3 m/s until a preferred speed was reported by the participant. 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) [30]. The rationale for selecting the running speeds was to avoid the transition speed between walking and running reported around 2.0 m/s [31]. After a short rest and when the participants reported no exertion based on a 20-point rating of perceived exertion (RPE) scale [32], the running trials were started; first the preferred speed running (PSR) and after a rest interval, the FSR. Once each running trial began, a few seconds acclimatization period was given and immediately following this, 3-dimensional marker trajectories were recorded for 30 s.

2.3. Data analysis

Retroreflective markers were identified and labeled within the Qualisys Track Manager software. Data processing and calculating 3-dimensional joint and segment angles were performed using Visual3D software (C-Motion®, Rockville, MD, USA). Kinematic data were low pass filtered, using a fourth-order Butterworth filter with a cut-off frequency of 9 Hz. The trunk and pelvis motions were defined relative to the global axis system, and knee joint motions as the shank relative to the thigh, using the Cardan angle sequence of X-Y-Z. For trunk and pelvis, positive values about the global Y-axis represent lateral flexion and lateral pelvic drop toward the stance leg, respectively. The positive value about the global X-axis for the trunk is extension and for the pelvis is posterior tilt. Positive values about X, Y, and Z local axis system for knee joint are extension, adduction, and internal rotation, respectively. Variables of interest included the magnitude of peak angles extracted from the stance phase:

1 Knee flexion, valgus, and internal rotation
2 Trunk forward flexion and trunk lateral flexion toward the stance leg (ipsilateral trunk flexion)
3 Pelvis anterior tilt (anterior pelvic tilt) and lateral flexion away from the stance leg (contralateral pelvic drop)

Moreover, the range of motion (RoM) of the trunk and pelvis in sagittal and frontal and RoM of the knee joint in three planes of motion was assessed during the stance phase.

For each running trial, all of these variables were extracted from the stance phase of all cycles (except first and last cycles) and then averaged. Data reduction was performed using a custom MATLAB program (version. 2018a, The MathWorks Inc, Natick, MA); all kinematic data was time-normalized to 100 % of the stance phase (101 data points).

2.4. Statistical analysis

All statistical analyses were performed in SPSS software (version 21; SPSS Inc., Chicago, IL, USA). An independent *t*-test was used to compare demographic characteristics between groups. The kinematic variables were compared between groups at PSR and FSR using a 2 × 2 (Group × Trial) mixed-model repeated-measures analysis of variance (ANOVA) with the trial as the repeated measure. Partial eta squared was reported as an effect size measure for all interaction and main effects. Using the guideline proposed by Cohen, the values of 0.01, 0.06, and 0.14 were interpreted as small, medium, and large effects, respectively [33]. The significance level for all analyses was set at $p \leq 0.05$.

3. Results

3.1. Subject characteristics

Both PFP and control groups were statistically similar in terms of age, height, weight, and preferred running speed (Table 1). There was a reduction trend in treadmill speed at PSR for the PFP compared with the control group ($p = 0.057$).

Table 1
Basic characteristics of participants 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 PSR (m/s)	2.10 ± 0.10	2.23 ± 0.22	0.057

PFP: Patellofemoral pain; PSR: preferred speed running.

3.2. Peak angular measurements

Descriptive statistics related to peak kinematic variables for both groups and at two running trials are shown in Table 2. Repeated-measures ANOVA results indicated that there was no significant group by trial interaction and also no main effect for group for peak kinematic variables ($P > 0.05$) (Table 2). A significant main effect for trial indicated that increases in forward trunk flexion, contralateral pelvic drop, anterior pelvic tilt, knee flexion, knee valgus, and knee internal rotation occurred at FSR compared with PSR ($P < 0.05$).

3.3. Range of motion measurements

Descriptive statistics related to RoM kinematic variables for both groups and at two trials are shown in Table 3. Repeated-measures ANOVA results for kinematic parameters related to RoM measurements indicated that there was no significant group by trial interaction for RoM measurements ($P > 0.05$) (Table 3). For the main effect of group, the PFP group exhibited less pelvis frontal plane RoM and greater knee frontal plane RoM compared with the control group ($P \leq 0.05$). There was a trend toward less knee sagittal plane RoM in PFP compared with the control group ($P = 0.061$) (Table 3). A significant main effect for trial indicated that increases in pelvis frontal plane RoM and knee transverse plane RoM occurred at FSR compared with PSR ($P < 0.05$) (Table 3).

4. Discussion

The purpose of this study was to compare trunk, pelvis, and knee joint kinematics (peak angular and RoM measurements) between individuals with and without PFP during running at preferred and fixed speeds.

The PFP group showed slower speed at PSR compared with the healthy group. This result is consistent with previous studies that have reported individuals with PFP adopt slower gait speed to reduce knee extensor moment, ground reaction force, or loading of the lower limb [11,12].

The PFP group displayed less pelvis frontal plane RoM and greater knee frontal plane RoM compared with the control group. On closer inspection of the data, we realized that the pelvic motion was decreased in both directions of the frontal plane (contralateral pelvic drop and rise). No differences in peak contralateral pelvic drop or trunk kinematics in frontal plane (peak ipsilateral trunk lean and trunk frontal plane RoM) were found between PFP and control groups. These findings may be indicative of a strategy through which the body attempts to minimize lateral displacements of the trunk and pelvis and increase core stabilization. There is strong evidence showing hip abductor weakness in females with PFP [22,34]. It has been theorized that in the presence of hip abductor weakness, the pelvis tends to drop on the contralateral side [12,16,23]. Another hypothesis is that the individuals with PFP compensate for hip abductor weakness by leaning the trunk toward the stance leg and elevating the pelvis on the contralateral side [14]. Contrary to both hypotheses, the PFP group in the current study seems to reduce the magnitude of both contralateral pelvic drop and rise, and also prevents increased lateral trunk lean to restrain further dynamic

Table 2
Peak kinematics of trunk, pelvis, and knee joint (mean ± SD) at FSR and PSR in those with and without PFP.

Peak kinematic variables (°)	Groups	Mean ± SD		Repeated-Measure ANOVA Results P-value (η_p^2)		
		FSR	PSR	Group × Trial	Group	Trial
Ipsilateral trunk flexion	Control	2.73 ± 1.33	2.61 ± 1.28	0.319 (0.03)	0.664 (0.006)	0.100 (0.08)
	PFP	3.10 ± 1.60	2.64 ± 1.50			
Forward trunk flexion	Control	−8.68 ± 3.98	−6.88 ± 3.40	0.655 (0.006)	0.253 (0.04)	<0.001* (0.68)
	PFP	−7.39 ± 3.63	−5.38 ± 3.17			
Contralateral pelvic drop	Control	−5.14 ± 2.30	−4.53 ± 2.42	0.275 (0.03)	0.208 (0.04)	0.004* (0.23)
	PFP	−3.96 ± 2.46	−3.67 ± 2.23			
Anterior pelvic tilt	Control	−12.31 ± 7.10	−11.55 ± 6.06	0.228 (0.04)	0.640 (0.007)	0.011* (0.18)
	PFP	−11.91 ± 6.69	−9.87 ± 6.52			
Knee flexion	Control	−41.38 ± 4.91	−39.87 ± 4.71	0.672 (0.006)	0.523 (0.01)	<0.001* (0.36)
	PFP	−40.21 ± 4.67	−38.97 ± 4.71			
Knee valgus	Control	−3.50 ± 2.60	−3.08 ± 2.46	0.526 (0.01)	0.691 (0.005)	0.016* (0.17)
	PFP	−3.13 ± 4.96	−2.44 ± 4.32			
Knee internal rotation	Control	1.68 ± 5.15	0.89 ± 5.61	0.364 (0.02)	0.607 (0.008)	<0.001* (0.46)
	PFP	2.98 ± 7.31	1.86 ± 7.24			

PFP: Patellofemoral pain; FSR: fixed speed running; PSR: preferred speed running. η_p^2: Partial eta-squared.
* Significant trial effect, P < 0.05.

Table 3
RoM of trunk, pelvis, and knee joint (mean ± SD) at FSR and PSR in those with and without PFP.

Range of Motion (°)	Group	Mean ± SD		Repeated-Measure ANOVA Results P-value (η_p^2)		
		FSR	PSR	Group × Trial	Group	Trial
Trunk sagittal plane	Control	3.02 ± 1.08	3.01 ± 1.17	0.607 (0.008)	0.785 (0.002)	0.552 (0.01)
	PFP	2.98 ± 0.85	2.88 ± 0.74			
Trunk frontal plane	Control	3.64 ± 1.27	3.93 ± 1.36	0.283 (0.03)	0.671 (0.006)	0.291 (0.03)
	PFP	3.61 ± 1.19	3.61 ± 1.15			
Pelvis sagittal plane	Control	4.93 ± 1.60	5.27 ± 1.70	0.139 (0.06)	0.301 (0.03)	0.723 (0.004)
	PFP	4.64 ± 1.58	4.43 ± 1.75			
Pelvis frontal plane	Control	8.35 ± 2.95	7.55 ± 2.53	0.882 (0.001)	0.050† (0.11)	<0.001* (0.42)
	PFP	6.84 ± 1.57	6.09 ± 1.43			
Knee sagittal plane	Control	29.27 ± 5.14	28.24 ± 4.55	0.318 (0.03)	0.061 (0.10)	0.580 (0.01)
	PFP	25.89 ± 4.10	26.19 ± 4.13			
Knee frontal plane	Control	5.74 ± 1.83	5.39 ± 2.11	0.703 (0.005)	0.030† (0.13)	0.064 (0.10)
	PFP	7.30 ± 2.01	6.78 ± 2.05			
Knee transverse plane	Control	15.18 ± 4.28	14.22 ± 3.10	0.760 (0.003)	0.605 (0.008)	<0.013* (0.17)
	PFP	16.00 ± 4.78	14.78 ± 3.76			

PFP: Patellofemoral pain; FSR: fixed speed running; PSR: preferred speed running. η_p^2: Partial eta-squared.
† Significant group effect, P ≤ 0.05.
* Significant trial effect, P < 0.05.

malalignment of the knee joint in this motion plane; because it has been suggested that instability of the trunk and pelvis as core segments could adversely affect the moments acting on the knee joint and therefore the PF joint stress [9]. Despite this presumed stabilization strategy, however, the knee frontal plane RoM is still greater in PFP compared with the control group; but it should be noted that there was no significant difference in peak knee valgus angle. Moreover, on closer inspection of the data, it was observed that greater knee frontal plane RoM in the PFP group was due to increased knee varus. With these in mind, adopted core stabilization strategy in the PFP group may aim at preventing excessive knee valgus, which is reported as a common finding in females with PFP [35].

While pelvis and knee frontal plane RoM showed significant differences between PFP and healthy groups, no significant differences were observed in peak contralateral pelvic tilt or peak knee valgus. Despite the existing theories or evidence suggesting the relationship between hip abductor weakness and increased pelvic drop [10,14] or knee valgus [36–38] in participants with PFP, there is contradictory evidence showing hip abductor strength and pelvis, hip and knee kinematics are not well correlated [39–42], and this might also be a reason for finding no between-group differences in peak contralateral pelvic drop, ipsilateral trunk lean or knee abduction.

Another possible explanation for non-significant differences in trunk and also other pelvis kinematic variables may be attributed to the task, as the studies using single-leg squat [43], stepping maneuver [44], and single-leg triple-hop test [45] to investigate trunk and pelvis kinematics in patients with PFP compared with healthy controls have found significant differences. The running task in the current study may not have been challenging enough to elicit between-group differences. These findings are confirmed with those of Bazett-Jones et al. [13] and Noehren et al. [18] that reported no significant differences in trunk and pelvis kinematics between PFP and control groups.

Peak knee flexion was similar between groups, which is in agreement with several previous studies [13,16,17], and in contrast to Dierks et al. [14], who reported less peak knee flexion in the PFP group compared with controls; however, there was a trend toward less knee sagittal plane RoM in PFP compared with the control group. Less knee sagittal plane ROM could be a protective mechanism to reduce PF joint reaction force [11,12,46].

There was also no significant group difference for peak knee valgus. Our finding, which is in agreement with several previous studies [14–16, 19], is in contrast to Bazett-Jones et al. [13], who reported greater knee valgus in the PFP compared with the control group; however, significantly greater knee frontal plane RoM was observed in PFP compared with the control group. Although on closer inspection of the data it was observed that increased knee frontal plane RoM was due to increased knee varus, altered knee frontal plane kinematics can influence the magnitude and direction of the PF joint reaction force through increasing or decreasing the Q-angle and, therefore, articular contact area and contact pressure of the PF joint [9].

Significant or marginally significant main effects of group (pelvis frontal plane RoM, knee frontal plane RoM, and knee sagittal plane RoM) showed medium to large magnitudes as presented by the effect sizes of 0.11, 0.13, and 0.10 respectively using partial eta squared [33].

Non-significant results showed very small effect sizes.

Knee transverse plane kinematics were not different between groups. This finding is in line with previous studies [13,14] and in contrast with Willson et al. [16], who reported less knee internal rotation in the PFP group. One possible reason for the lack of difference in peak knee internal rotation is that the amount of knee motion in the transverse plane during the gait is relatively small. Moreover, the ratio of the standard deviation to the mean for this variable in both groups at FSR and PSR is small. Considering this small signal-to-noise ratio, the detection of small differences in knee rotation is unlikely.

Both PFP and control groups showed increases in most of the kinematic variables at FSR compared with the PSR. The FSR was more than PSR, not only on average but also for each participant. Although this result could be due to the increasing demand at FSR compared with the PSR, this increasing demand did not result in exacerbating or finding more between-group differences.

The results of this study support the developing notion of the close relationship between core stability and lower extremity structure and pathology [25,36]. Clinical assessment and treatment approaches may benefit from considering a global program that focuses on pelvis kinematics in addition to the knee joint in individuals with PFP.

There are several limitations to our study that should be noted. First, the cross-sectional design in the present study does not allow us to establish a cause-and-effect relationship between PFP and kinematic changes. Prospective studies are essential to confirm the findings of the current study. Second, all participants wore standard shoes to minimize the confounding factors relating to footwear. Changing the footwear may affect the kinematics among participants who are not habituated to the standardized shoes. Third, participants in this study were females aged 18–35 years old recruited from the general population, so our findings may not be generalizable to males or females with different activity levels (e.g., runners) or age groups. Fourth, we just assessed kinematics among all biomechanical factors related to PFP. Future studies, including myoelectric activities and kinetic analysis using inverse dynamics and biomechanical models of the musculoskeletal system, are needed to delineate the different strategies that individuals with and without PFP have more noticeably adapted. Fifth, the reliability of kinematic marker placement and also kinematic outputs was not assessed in the current study, and further studies are needed to assess them.

5. Conclusion

It seems that the PFP group in the current study adopted some protective strategies to avoid PF joint pressure and pain during running. PFP group displayed less pelvis frontal plane RoM and greater knee frontal plane RoM during running; this may be suggestive of a rigid stabilization strategy through which the body attempts to increase core stability to prevent further frontal plane knee malalignment and, therefore the PF joint pressure. The PFP group tended to have less knee sagittal plane RoM compared with controls, which may be a protective mechanism aimed at decreasing PF joint reaction force. Increases in most of the kinematic variables occurred at FSR compared with the PSR in both PFP and healthy groups.

Declaration of Competing Interest

None.

Acknowledgments

The current article was extracted from the Ph.D. thesis written by Farzaneh Haghighat. This work was financially supported by Shiraz University of Medical Sciences (Grant number: 97-01-04-17431). We thank the scientific and financial support from Shiraz University of Medical Sciences, the Deputy for Research Affairs, and the School of Rehabilitation Sciences. The authors wish to thank Dr. Terrance John Mueller for reviewing the use of English in the manuscript.

References

[1] I.S. Davis, C. Powers, Patellofemoral pain syndrome: proximal, distal, and local factors—international research retreat, april 30–May 2, 2009, Baltimore, Maryland, J. Orthop. Sports Phys. Ther. 40 (3) (2010) A1–A48.
[2] K.M. Crossley, J.J. Stefanik, J. Selfe, N.J. Collins, I.S. Davis, C.M. Powers, et al., Patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester. Part 1: Terminology, definitions, clinical examination, natural history, patellofemoral osteoarthritis and patient-reported outcome measures, Br. J. Sports Med. 50 (14) (2016) 844–852 (2016).
[3] B.E. Smith, J. Selfe, D. Thacker, P. Hendrick, M. Bateman, F. Moffatt, et al., Incidence and prevalence of patellofemoral pain: a systematic review and meta-analysis, PLoS One 13 (1) (2018), e0190892.
[4] S.F. Dye, Patellofemoral pain current concepts: an overview, Sports Med. Arthrosc. 9 (4) (2001) 264–272.
[5] K.M. Crossley, Is Patellofemoral Osteoarthritis a Common Sequela of Patellofemoral Pain? BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine, 2014.
[6] L. Blond, L. Hansen, Patellofemoral pain syndrome in athletes: a 5.7-year retrospective follow-up study of 250 athletes, Acta Orthop. Belg. 64 (4) (1998) 393–400.
[7] P. Kannus, A. Natri, T. Paakkala, M. JÄRvinen, An outcome study of chronic patellofemoral pain syndrome. Seven-year follow-up of patients in a randomized, controlled trial, JBJS 81 (3) (1999) 355–363.
[8] C.M. Powers, E. Witvrouw, I.S. Davis, K.M. Crossley, Evidence-based framework for a pathomechanical model of patellofemoral pain: 2017 patellofemoral pain consensus statement from the 4th international patellofemoral pain research retreat, Manchester, UK: part 3, Br. J. Sports Med. (2017) bjsports-2017-098717.
[9] C.M. Powers, The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective, J. Orthop. Sports Phys. Ther. 33 (11) (2003) 639–646.
[10] C.M. Powers, The influence of abnormal hip mechanics on knee injury: a biomechanical perspective, J. Orthop. Sports Phys. Ther. 40 (2) (2010) 42–51.
[11] C.M. Powers, P.-Y. Chen, S.F. Reischl, J. Perry, Comparison of foot pronation and lower extremity rotation in persons with and without patellofemoral pain, Foot Ankle Int. 23 (7) (2002) 634–640.
[12] C.M. Powers, J.G. Heino, S. Rao, J. Perry, The influence of patellofemoral pain on lower limb loading during gait, Clin. Biomech. 14 (10) (1999) 722–728.
[13] D.M. Bazett-Jones, S.C. Cobb, W.E. Huddleston, K.M. O'Connor, B.S. Armstrong, J. E. Earl-Boehm, Effect of patellofemoral pain on strength and mechanics after an exhaustive run, Med. Sci. Sports Exerc. 45 (7) (2013) 1331–1339.
[14] T.A. Dierks, K.T. Manal, J. Hamill, I. Davis, Lower extremity kinematics in runners with patellofemoral pain during a prolonged run, Med. Sci. Sports Exerc. 43 (4) (2011) 693–700.
[15] B. Noehren, Z. Sanchez, T. Cunningham, P.O. McKeon, The effect of pain on hip and knee kinematics during running in females with chronic patellofemoral pain, Gait Posture 36 (3) (2012) 596–599.
[16] J.D. Willson, I.S. Davis, Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands, Clin. Biomech. 23 (2) (2008) 203–211.
[17] A.D. Wirtz, J.D. Willson, T.W. Kernozek, D.-A. Hong, Patellofemoral joint stress during running in females with and without patellofemoral pain, Knee 19 (5) (2012) 703–708.
[18] B. Noehren, M.B. Pohl, Z. Sanchez, T. Cunningham, C. Lattermann, Proximal and distal kinematics in female runners with patellofemoral pain, Clin. Biomech. 27 (4) (2012) 366–371.
[19] R.B. Souza, C.M. Powers, Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain, J. Orthop. Sports Phys. Ther. 39 (1) (2009) 12–19.
[20] T.F. Besier, G.E. Gold, S.L. Delp, M. Fredericson, G.S. Beaupré, The influence of femoral internal and external rotation on cartilage stresses within the patellofemoral joint, J. Orthop. Res. 26 (12) (2008) 1627–1635.
[21] H.-L. Teng, C.M. Powers, Sagittal plane trunk posture influences patellofemoral joint stress during running, J. Orthop. Sports Phys. Ther. 44 (10) (2014) 785–792.
[22] M.R. Prins, P. Van Der Wurff, Females with patellofemoral pain syndrome have weak hip muscles: a systematic review, Aust. J. Physiother. 55 (1) (2009) 9–15.
[23] R.W. Willy, K.T. Manal, E.E. Witvrouw, I.S. Davis, Are mechanics different between male and female runners with patellofemoral pain? Med. Sci. Sports Exerc. 44 (11) (2012) 2165.
[24] J.-F. Esculier, J.-S. Roy, L.J. Bouyer, Lower limb control and strength in runners with and without patellofemoral pain syndrome, Gait Posture 41 (3) (2015) 813–819.
[25] M. Biabanimoghadam, A. Motealleh, S.M. Cowan, Core muscle recruitment pattern during voluntary heel raises is different between patients with patellofemoral pain and healthy individuals, Knee 23 (3) (2016) 382–386.
[26] R. Arjun, R. Kishan, M. Dhillon, D. Chouhan, Reliability of clinical methods in evaluating patellofemoral pain syndrome with malalignment, Int. J. Res. Orthop. 3 (3) (2017) 334–338.
[27] H. Negahban, M. Pouretezad, M.J.S. Yazdi, S.M. Sohani, M. Mazaheri, M. Salavati, et al., Persian translation and validation of the Kujala Patellofemoral Scale in patients with patellofemoral pain syndrome, Disabil. Rehabil. 34 (26) (2012) 2259–2263.

[28] A. Cappozzo, A. Cappello, U.D. Croce, F. Pensalfini, Surface-marker cluster design criteria for 3-D bone movement reconstruction, IEEE Trans. Biomed. Eng. 44 (12) (1997) 1165–1174.

[29] F. Alvim, L. Cerqueira, A.D.A. Netto, G. Leite, A. Muniz, Comparison of five kinematic-based identification methods of foot contact events during treadmill walking and running at different speeds, J. Appl. Biomech. 31 (5) (2015) 383–388.

[30] B.C. Heiderscheit, J. Hamill, R.E. Van Emmerik, Variability of stride characteristics and joint coordination among individuals with unilateral patellofemoral pain, J. Appl. Biomech. 18 (2) (2002) 110–121.

[31] A. Rotstein, O. Inbar, T. Berginsky, Y. Meckel, Preferred transition speed between walking and running: effects of training status, Med. Sci. Sports Exerc. 37 (11) (2005) 1864.

[32] R. Arvari, H. Dehghan, A. Haghi, H. Rajabivardanjan, Validity and reliability of the persian version of borg RPE in two 10-0 and 20-6 scales, Int. J. Healthc. Inf. Syst. Inform. 9 (8) (2013) 851–858.

[33] J. Cohen, Statistical Power for the Behavioural Sciences, Lawrence Erlbaum, Hilsdale, NY, 1988.

[34] J. Van Cant, C. Pineux, L. Pitance, V. Feipel, Hip muscle strength and endurance in females with patellofemoral pain: a systematic review with meta-analysis, Int. J. Sports Phys. Ther. 9 (5) (2014) 564.

[35] C.M. Powers, E. Witvrouw, I.S. Davis, K.M. Crossley, Evidence-based framework for a pathomechanical model of patellofemoral pain: 2017 patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester, UK: part 3, Br. J. Sports Med. (2017) 1713–1723.

[36] J.D. Willson, C.P. Dougherty, M.L. Ireland, I.M. Davis, Core stability and its relationship to lower extremity function and injury, JAAOS-J. Am. Acad. Orthopaedic Surg. 13 (5) (2005) 316–325.

[37] J.H. Hollman, B.E. Ginos, J. Kozuchowski, A.S. Vaughn, D.A. Krause, J.W. Youdas, Relationships between knee valgus, hip-muscle strength, and hip-muscle recruitment during a single-limb step-down, J. Sport Rehabil. 18 (1) (2009) 104–117.

[38] C.A. Jacobs, T.L. Uhl, C.G. Mattacola, R. Shapiro, W.S. Rayens, Hip abductor function and lower extremity landing kinematics: sex differences, J. Athl. Train. 42 (1) (2007) 76.

[39] J.J. Hannigan, L.R. Osternig, L.-S. Chou, Sex-Specific Relationships between hip strength and hip, pelvis, and trunk kinematics in healthy runners, J. Appl. Biomech. 34 (1) (2018) 76–81.

[40] R.B.K. Brund, S. Rasmussen, R.O. Nielsen, U.G. Kersting, U. Laessoe, M. Voigt, The association between eccentric hip abduction strength and hip and knee angular movements in recreational male runners: an explorative study, Scand. J. Med. Sci. Sports 28 (2) (2018) 473–478.

[41] L.A. Bolgla, T.R. Malone, B.R. Umberger, T.L. Uhl, Hip strength and hip and knee kinematics during stair descent in females with and without patellofemoral pain syndrome, J. Orthop. Sports Phys. Ther. 38 (1) (2008) 12–18.

[42] R.B. Souza, C.M. Powers, Predictors of hip internal rotation during running, Am. J. Sports Med. 37 (3) (2009) 579–587.

[43] T.H. Nakagawa, E.T. Moriya, C.D. Maciel, F.V. Serrao, Trunk, pelvis, hip, and knee kinematics, hip strength, and gluteal muscle activation during a single-leg squat in males and females with and without patellofemoral pain syndrome, J. Orthop. Sports Phys. Ther. 42 (6) (2012) 491–501.

[44] T.H. Nakagawa, E. Moriya, C.D. Maciel, A. Serrao, Frontal plane biomechanics in males and females with and without patellofemoral pain, Med. Sci. Sports Exerc. 44 (9) (2012) 1747–1755.

[45] A.C. Dos Reis, J.C.F. Correa, A.S. Bley, N.Dd.A. Rabelo, T.Y. Fukuda, P.R. G. Lucareli, Kinematic and kinetic analysis of the single-leg triple hop test in women with and without patellofemoral pain, J. Orthop. Sports Phys. Ther. 45 (10) (2015) 799–807.

[46] F. Halabchi, M. Abolhasani, M. Mirshahi, Z. Alizadeh, Patellofemoral pain in athletes: clinical perspectives, Open Access J. Sports Med. 8 (2017) 189.