Title: Are mechanics different between male and female runners with patellofemoral pain?

Short Title: Sex-specific mechanics in patellofemoral pain

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Abstract

Introduction: Patellofemoral pain (PFP) has often been attributed to abnormal hip and knee mechanics in females. To date, there have been few investigations of the hip and knee mechanics of males with PFP. The purpose of this study was to compare the lower extremity mechanics and alignment of male runners with PFP with healthy male runners and female runners with PFP. We hypothesized that males with PFP would move with greater varus knee mechanics compared with male controls and compared with females with PFP. Further, it was hypothesized that males with PFP would demonstrate greater varus alignment.

Methods: A gait and single leg squat analysis was conducted on each group (18 runners per group). Measurement of each runner’s tibial mechanical axis was also recorded. Motion data were processed using Visual 3D (CMotion, Bethesda, Md., USA). Analyses of Variance were used to analyze the data.

Results: Males with PFP ran and squatted in greater peak knee adduction and demonstrated greater peak knee external adduction moment compared with healthy male controls. In addition, males with PFP ran and squatted with less peak hip adduction and greater peak knee adduction compared with females with PFP. The static measure of mechanical axis of the tibial was not different between groups. However, a post-hoc analysis revealed that males with PFP ran with greater peak tibial segmental adduction.

Conclusion: Males with PFP demonstrated different mechanics during running and during a single leg squat compared with females with PFP and with healthy males. Based upon the results of this study, therapies for PFP may need to be sex-specific.

KEY WORDS: Patellofemoral Pain, Running, Biomechanics, Sex Differences

Introduction

Paragraph Number 1: Running is one of the most popular forms of exercise with upwards of 16 million Americans participating.(20) However, runners report an alarmingly high annual injury rate of up to 79.3%.(36) Patellofemoral pain (PFP) is the most prevalent injury among runners and is characterized by pain under or around the kneecap.(32) Unfortunately, in more than 90% of individuals with PFP, this pain becomes chronic.(31) Individuals with chronic PFP may be at greater risk for developing patellofemoral osteoarthritis later in life.(34,37) As with many knee injuries, females are twice as likely to experience PFP compared with males.(32)

Paragraph Number 2: Recent studies have suggested that abnormal hip and knee mechanics are associated with PFP in females.(6,23-26,28-30,39-41) These abnormal mechanics include excessive peak contralateral pelvic drop, (6,39,41) peak hip adduction, (6,25,39,41) and peak hip internal rotation (6,28,29) and decreased peak knee adduction.(25) In combination, these motions result in dynamic valgus of the knee, resulting in lateral patellar tracking and an increase in the loading forces on the lateral aspect of the patellofemoral joint.(3,12,14,23,24) Importantly, these abnormal mechanics appear to be present in females with PFP across a variety of activities, including both running and during a single leg squat.(6,28,29,39,40) Thus, evaluation of single leg squat mechanics is often used clinically to make extrapolations to running mechanics in individuals with PFP.(40)

Paragraph Number 3: Preliminary investigations suggest that the gait mechanics of males with PFP may differ from females with PFP. In a mixed sex cohort of runners with PFP, Dierks et al. (2008) reported that the females with PFP ran with increased hip adduction and internal rotation, consistent with previous literature.(6) However, the few males with PFP in the cohort actually exhibited decreased hip adduction during running.(6) The decreased hip adduction may indicate that the males ran with greater knee varus. Thijs et al. (2007) found that military recruits (predominately male) who developed PFP prospectively demonstrated a more laterally deviated center of pressure during walking than healthy controls.(33) A more lateral center of pressure is associated with a higher external knee adduction moment during walking, suggesting a more adducted knee (7). Decreased hip adduction, coupled with a laterally deviated center of pressure, may indicate a varus aligned lower extremity during gait in males with PFP. Compared with a lower extremity in dynamic valgus, a lower extremity in dynamic varus may have distinctly different effects on the mechanics of the patellofemoral joint. Specifically, medial maltracking may result from increasing dynamic varus alignment by either increasing knee adduction or knee internal rotation.(3,12,14) These motions may be influenced proximally by decreasing hip adduction and/or hip internal rotation.

Paragraph Number 4: Despite the potential differences in dynamic alignment in individuals with and without PFP, the relationship between static frontal plane alignment of the knee and PFP is unclear. Witvrouw and colleagues found no prospective evidence supporting the role of static frontal plane alignment of the tibiofemoral joint in the development of PFP in a mixed gender cohort.(42) In contrast, Milgrom et al. (1991)

reported that individuals who had greater varus alignment were more than twice as likely to develop PFP than those who had normal or valgus alignment.(17) The reason for this discrepancy between the two studies may be due to differences in subject selection. Indeed, Witvrouw and colleagues studied a mixed-gender cohort, whereas Milgrom et al., evaluated males enrolled in basic military training. Since it has been established that healthy males have been shown to have greater static knee varus than healthy females, differences in alignment between individuals with and without PFP in Witvrouw et al. may have been masked by the mixed gender cohort. (22)

Paragraph Number 5: Previously, static varus alignment has been shown to relate closely to increased dynamic varus alignment, as well as a greater knee external adduction moment during walking in young, healthy males.(1) A greater knee external adduction moment would act on the frontal plane of the knee, potentially resulting in an even greater increase in dynamic knee varus during gait. In fact, one of the best predictors of knee external adduction moment is indeed static varus alignment.(1) Thus, determination of static alignment in individuals with PFP may be critical in understanding the nature of their dynamic alignment during running and squatting.

Paragraph Number 6: Therefore, we sought to compare the lower extremity mechanics and structure of males with PFP to male controls and females with PFP during running and during a single leg squat. We hypothesized that males with PFP would move with less peak contralateral pelvic drop (CPD), hip adduction (HADD), hip internal rotation (HIR), but with greater knee adduction (KADD) and higher associated knee external abduction moment than healthy males and females with PFP. We further hypothesized that males with PFP would have greater static varus alignment when compared with healthy males and females with PFP.

Methods

Subjects

Paragraph Number 7: The data collection protocol and informed consent document were approved by the University of Delaware Human Subjects Research Board. In order to participate, both written and verbal informed consent was obtained from each volunteer. An *a-priori* power analysis was conducted using data from pilot work for this study. Using the variable with the highest standard deviation, hip internal rotation, it was revealed that 20 subjects per group (effect size=1.04, α= 0.05, β=0.20) were required to adequately power this study. The subject groups consisted of males with PFP, matched male controls, and females with PFP. Healthy females were not collected; comparisons of the running and squatting mechanics in females with and without PFP are readily available in the literature.(6,25,28,29,39)

Paragraph Number 8: Runners between the ages of 18 and 40 years old, currently running at least 10 km per week, able to comfortably run at a 3.35 m/s pace with a non-antalgic gait pattern, and free of any lower extremity surgeries were recruited for the study. Subjects were recruited from the University of Delaware student body, area running clubs, and local races. For participants with PFP, a diagnosis was determined during a musculoskeletal screening session by a licensed physical therapist who is board certified in orthopedics (co-author RW). All participants with PFP were required to have patellofemoral pain for at least the previous 3 months prior to their data collection. PFP was operationally defined as retropatellar or peripatellar pain that was self-rated at least a “3” on a visual analog scale of “0” to “10.” This pain was required to be present during running and at least one other activity. The onset of pain was required to be atraumatic in nature. All volunteers with patellofemoral instability, with other knee diagnoses, or who were otherwise unhealthy were excused. Prior rehabilitation for knee pain was not an exclusion criterion. When knee pain was bilateral, the knee with the highest self-rated pain was analyzed. When pain was equal bilaterally, the most dominant limb (defined as the limb used to kick a soccer ball) was analyzed. Males with PFP were matched with healthy male volunteers and females with PFP based upon average weekly running distance and age.

Paragraph Number 9: Qualified volunteers were invited to participate in the study. Subjects first completed the Lower Extremity Functional Scale (LEFS) to assess overall functional status. The LEFS requires subjects to rate the extent that their knee pain limits their ability to perform 20 separate activities. Each answer is based on a scale of “1” to “4”, with ”1” corresponding with an inability to perform a task and “4” corresponding with no difficulty performing a task. The LEFS has been shown to be a reliable and valid means to classify functional limitations secondary to PFP.(4)

Paragraph Number 10: Subjects were then prepared for motion analysis. Thirty retroreflective markers were attached to the pelvis and the affected lower extremity to analyze running and SLS kinematics. Subjects wore standardized neutral running shoes (Nike Pegasus, Beaverton, Ore) in order to control for the effect of footwear on mechanics. All kinematic and kinetic data were sampled at 200 Hz and 1000 Hz, respectively. Three-dimensional marker coordinates were captured with an 8 camera

Vicon Mx system (VICON, Oxford, UK). To establish segment coordinate systems, a standing calibration trial was collected while the subject stood on a force platform (Bertec, Worthington, OH, USA) mounted in the center of the capture volume. Next, a functional hip trial was collected to determine the hip joint center.(9) Running kinematic and kinetic data were then collected as subjects traversed a 25-meter runway at 3.35 m/sec (8 min/mile). All subjects were asked during the collection of the running data if the fixed running speed of 3.35 m/s was a comfortable pace. No subjects indicated that the test speed was uncomfortable. Subjects were monitored closely for targeting of the force platform during all running trials. Lastly, single leg squat data were collected as subjects performed a squat to approximately 60 degrees knee flexion while standing on the center of the force platform. While squatting, subjects were asked to maintain an arm position of approximately 90 degrees of shoulder abduction. Five trials per activity were collected for later analysis. Subjects performed the squatting maneuver to a 1 Hz count to standardize the speed of the squatting maneuver.

Paragraph Number 11: The measurement of tibial mechanical axis was obtained as per Barrios et al.(1) For this measure, each subject was asked to assume side by side stance with even weight distribution (Figure 1). The proximal arm of a caliper inclinometer (Isomed, Portland, OR, USA) was aligned with the most prominent aspect of the tibial tuberosity. The distal arm was aligned with the center of the neck of the talus, yielding an angle in respect to vertical. Three trials were collected. The tibial mechanical axis was recorded to the nearest degree and the mean of the three trials was used for eventual analysis. This technique has been shown to have a high correlation to full-length radiographs quantifying the mechanical axis of the lower extremity(*r=0.80*).(10)

Paragraph Number 12: All kinematic and kinetic data were filtered with an 8- and 50-Hz, low-pass, fourth-order, zero-lag Butterworth filter, respectively. 3-D joint and segment angles were calculated with Visual 3-D software (C-Motion Bethesda, MD) using an X-Y-Z Euler angle rotation sequence. Internal joint moments were calculated utilizing segment inertial properties as per Dempster et al.(5) Internal joint moments were normalized to body mass and height. Internal knee abduction moment was negated to represent external knee adduction moment.

Paragraph Number 13: Only the stance phase of running was analyzed. For single leg squat data, the event was defined as beginning when knee flexion was initiated and concluding when 60 degrees of knee flexion was reached. For each participant, single leg squat mechanics were analyzed at the index of mean peak knee flexion calculated from their running data. During running, peak KADD and external knee adduction moment typically occurs at peak knee flexion. Therefore, this subject-specific index for the single leg squat was chosen to facilitate direct comparisons between the two tasks. By evaluating at the same knee flexion angle, the feasibility of using the single leg squat as a clinical screen for running mechanics could be evaluated. Customized software (LabVIEW 8.0, National Instruments, Austin, TX, USA) was used to extract the discrete variables of interest from five individual curves for the motion files. Means and standard deviations of these values were calculated. Finally, individual mean curves were time normalized and ensemble curves were created for display of the group mean data.

Paragraph Number 14: The variables of interest were HADD, HIR, CPD, KADD, external knee adduction moment, and tibial mechanical axis. To better understand the contributors to KADD, we performed a post hoc assessment of tibial and femoral segment data during the two tasks. To conduct the post hoc analysis, the tibial and femoral segments were referenced to the lab coordinate system during running (indexed to the primary outcome variable peak knee adduction) and squatting (indexed to individual peak knee flexion angle during running). Statistical analyses were conducted using SPSS (IBM, Chicago, Ill., USA). Normality of the data was assessed with a Shapiro-Wilk test. Two separate analyses of variance (ANOVA) (group (3) X activity) were conducted to compare differences in mechanics, strength, and structure. Statistical significance was determined at $\alpha = 0.05$ and a trend was defined as an $\alpha \leq 0.10$.

Results

Paragraph Number 15: A total of 54 qualified subjects (18 per group) participated in this study. While originally powered for 60 subjects, we opted to halt data collection once statistical power had been reached in the main outcome variables. The three groups were not statistically different in regards to age and mileage (Table 1). However, body mass index was significantly higher in males with PFP compared with control males and females with PFP. Interestingly, males with PFP were considered overweight, as per World Health Organization guidelines.(43) In addition, females with PFP had a significantly greater level of chronicity of PFP than males with PFP. However, there were no differences in pain and LEFS scores between males and females with PFPS.

Paragraph Number 16: During running, several differences were detected between the three groups (Table 2). Contrary to our hypotheses, males with PFP ran with greater peak CPD than healthy male controls (p=0.002, F=11.881) (Figure 2a). Interestingly, no differences were detected in peak HADD (p=0.394, F=0.745) and peak HIR (p=0.557, F=0.351) (Figure 2b, c) between the injured and healthy male groups. However, males with PFP ran with greater peak KADD (p=0.029, F=5.224) and greater peak external knee adduction moment (p=0.041, F=4.501) than male controls, as hypothesized (Figure 3a, b). Peak KADD was greater in the males with PFP (p=0.018, F=6.136) and peak HADD was less than females with PFP (p=0.000, F=34.319). Despite these differences, both males and females with PFP ran with similar peak CPD (p=0.19, F=1.772).

Paragraph Number 17: During the single leg squat, injured males demonstrated greater KADD (p=0.021, F=5.855) than their healthy counterparts (Table 3). However, external knee adduction moment was similar between both male groups. Males with PFP squatted with greater KADD (p=0.000, F=23.279) than females with PFP who squatted with an abducted knee. As hypothesized, males with PFP squatted with less HADD than their injured male counterparts (p=0.007, F=8.097).

Paragraph Number 18: Surprisingly there were no differences in the tibial mechanical axis when comparing males with PFP to either healthy males or to females with PFP (Table 2). Thus, while peak KADD during the two tasks was greater in the males with PFP, the mechanical axis of the tibia was not. While there was no difference in peak femoral adduction (running: p= 0.10, F= 2.931, squatting: p=0.46, F= 0.559), the males with PFP ran with greater tibial adduction than the controls ($p=0.05$, $F= 4.114$) (Table 2 and 3). Similarly, a trend towards greater tibial adduction in males with PFP during the single leg squat was noted ($p= 0.09$, $F= 2.879$). In contrast, females with PFP ran and squatted with greater femoral adduction ($p<0.000$, $F= 19.535$, $p= 0.001$, $F= 9.138$), respectively) when compared with the males with PFP. Interestingly, there was not a significant difference in tibial adduction between males and females with PFP during running ($p= 0.09$, $F= 2.971$) and squatting.

Discussion

Paragraph Number 19: We sought to determine if males with PFP run and squat differently than healthy males and females with PFP. The results of this study suggest that males with PFP run and squat with greater knee adduction, knee external adduction moment, and contralateral pelvic drop than healthy males. In contrast, males with PFP ran and squatted with less HADD compared to females with PFP. These differences in mechanics suggest that males and females with PFP may require different interventions.

Paragraph Number 20: Our findings suggest that males with PFP run and squat in excessive dynamic knee varum. Increasing knee varum dynamically will likely lead to a decrease in the quadriceps angle.(23) The quadriceps angle is defined as the angle formed by two lines: a) a line drawn between the anterior superior iliac spine and the midpoint of the patella, b) a line drawn between the tibial tuberosity and the midpoint of the patella. (23) Excessively decreasing the quadriceps angle has been shown to result in medial tracking of the patella while increasing medial patellofemoral joint stress.(3,12,14) In contrast, increasing the quadriceps angle (as seen in females with PFP) has been shown to increase lateral translation of the patella while increasing lateral patellofemoral joint stress.(3,12,14) Both decreasing and increasing the quadriceps angle can have a detrimental effect on the articular contact area of the patellofemoral joint.(3,12,14) In contrast to increasing the quadriceps angle, decreasing the quadriceps angle appears to decrease contact area to an even greater extent as the patella shifts to the smaller medial aspect of the trochlea.(3) Thus, *decreasing* the quadriceps angle can have an even larger effect on patellofemoral joint stresses than *increasing* the quadriceps angle an equal amount. (3,12) Thus, even the small differences noted in KADD between males with PFP and healthy males may have a large effect on patellofemoral joint stress. Chronically high patellofemoral stress may lead to overloading of the articular cartilage and subchondral bone, ultimately resulting in the pain associated with PFP. (3,8)

Paragraph Number 21: No differences were found between groups for the structural measure of tibial mechanical axis. This was somewhat surprising, especially considering the differences in dynamic alignment. The post-hoc analysis of segmental motion revealed greater tibial adduction in males with PFP when compared to healthy males (and a trend when compared to females with PFPS). This suggests that the greater peak KADD exhibited by males with PFP was more related to dynamic rather than static alignment. This is encouraging as mechanics are modifiable whereas structure is not easily changed without surgical intervention. In contrast, males with PFP demonstrated only a trend of increased dynamic tibial adduction, but a significantly more vertical femur compared with females with PFP. These mechanics may speak to the influence of different pelvic widths between sexes, necessitating increased femoral adduction in the females and resulting in a less adducted knee. We found a significant difference in CPD, yet no differences in HADD between males with and without PFP. This discrepancy is likely explained by the trend of decreased adduction of the femoral segment in the lab coordinate system, indicating a more vertical femur in males with PFP. Interestingly, an increase in CPD has been associated with higher external knee adduction moments in the medial knee osteoarthritis population during walking.(11,15) Thus, the excessive CPD exhibited by males with PFP may contribute to the higher knee external adduction moment, resulting in the higher KADD seen in males with PFP. While not assessed in the present study, variations in step width may also have an effect on the knee external adduction moment during running. For instance, a crossover gait pattern results in elevated frontal plane moments of the knee in healthy runners.(16) Future investigations should investigate if a males with PFP run with crossover gait pattern.

Paragraph Number 22: Intervention studies have suggested that dynamic hip and knee mechanics can be modified through neuromuscular re-education programs, such as gait retraining. (2,18,21,27,38) Neuromuscular treatment programs aimed at reducing KADD and knee external adduction moment may show promise in the treatment of PFP in male runners. For instance, cueing medial thrusting of the thigh or providing realtime feedback on the knee external adduction moment has been shown to reduce both KADD and the knee external adduction moment during walking in individuals.(2,27,38)

In contrast, cueing a reduction of excessive HADD has been shown to reduce abnormal hip mechanics and pain in female runners with PFP.(21)

Paragraph Number 23: It was interesting to note that mechanics were not entirely consistent within the male and female groups. In fact, 3 out of 18 males with PFP ran with excessive HADD and decreased KADD, similar to the group means of females with PFP. In contrast, 4 out of 18 females with PFP ran with reduced HADD and increased KADD, similar to the group means of males with PFP. Thus, while there were generally mean differences found between male and females with PFP, the mechanics of PFP during running are not exclusively sex-related. This finding highlights the importance of individualized gait analysis in the evaluation of patients with PFP.

Paragraph Number 24: During the single leg squat, males with PFP demonstrated greater KADD than healthy males or than females with PFP. Despite this difference, external knee adduction moments were similar between groups. Previously, females who would go on to develop PFP have been reported to demonstrate a higher knee external abduction moment during jump landing when compared to healthy females.(19) Thus, group differences in external knee adduction moment may only be present in activities that have higher ground reaction forces such as running (as seen in this study) or jumping. Future investigation of differences in jump landing mechanics in males with and without PFP and females with PFP may be warranted. Regardless, KADD was remarkably consistent across the two tasks for males with and without PFP. Based on this finding, it appears that the single leg squat may be a useful screening tool to assess dynamic varus mechanics in male runners with and without PFP.

Paragraph Number 25: We found that our males with PFP were generally heavier than the male controls. Matching the controls to the males with PFP for BMI would have resulted in an overweight reference group. Thus, all joint moments were normalized to body mass. Certainly, an increase in body mass may have a negative impact on loading of the patellofemoral joint. However, a recent meta-analysis found that BMI is not associated prospectively with PFP.(13) The cross-sectional design of the present study precludes any inference of causation. However, the elevated BMI in males with PFP may provide a hindrance to recovery from the injury in this cohort. Further study may be necessary in the relationship of excessive body mass index and PFP in male runners.

Paragraph Number 26: Limitations of this current study should be noted. First, this study is cross-sectional in design. Therefore, care should be taken to infer causation from these findings. For instance, the increased KADD noted in males with PFP may represent a movement strategy to reduce knee pain. Future investigations should have a prospective design to further investigate the mechanics in males with PFP found in this study. We also collected each subject's running mechanics at a prescribed running speed. While each subject attested to being comfortable running at the fixed running speed, running mechanics may be different if collected at their preferred running speed. Finally, we are only able to infer patellofemoral joint mechanics based on segmental motions of the thigh and lower leg. Therefore, kinematic imaging techniques, such as bi-plane fluoroscopy, are required to quantify the 3-D kinematics of the patellofemoral joint during running and other functional tasks in individuals with and without PFP.

Conclusion

Paragraph Number 27: In this cross-sectional study, males with PFP ran and squatted with increased knee adduction. In contrast, females with PFP ran and squatted with greater hip adduction and less knee adduction. These sex-specific mechanics suggest that males and females with PFP may need differing interventions.

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CONFLICT OF INTEREST

Paragraph Number 29: There are no conflicts of interest among any of the authors of this manuscript.

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Figure Captions

Figure 1: Measurement of the Tibial Mechanical Axis.

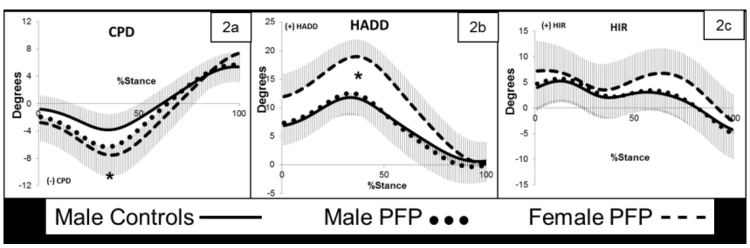

Figure 2: Hip kinematics during running. Error bars correspond to ±1 standard deviation. a) Contralateral pelvic drop (CPD). Note increased CPD for both males with PFP and females with PFP compared with male controls; b) Hip adduction (HADD). Note increased values for females with PFP only; c) Hip internal rotation (HIR): There were no differences between the 3 groups.

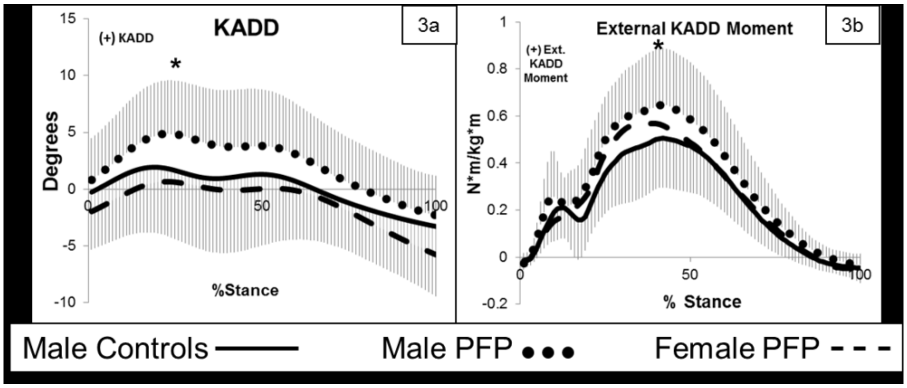

Figure 3: Frontal Plane knee mechanics during running. Error bars correspond to ±1 standard deviation. a) Knee adduction (KADD) and b) external KADD moment. Note that males with PFP ran in greatest peak KADD and, reflecting that alignment, Males with PFP ran with the greater peak KADD moment than control males, but not significantly different that females with PFP.

Table Captions

Table 1: Demographic information (mean(SD)) for the three subject groups. *signifies p>0.05. VAS= Visual analog scale, LEFS= Lower extremity functional scale.

	Male Controls	=> p <=	Males PFP	=> p <=	Females PFP
Age (years)	23.4(3.6)	0.36	24.7(4.9)	0.11	22.2(3.8)
Running (km/ wk)	29.5(20.0)	0.16	21.7(10.3)	0.48	24.6(14.2)
Body Mass Index (kg/m^2)	23.4(2.7)	0.028*	25.7(2.0)	<0.000	21.8(2.8)
Pain (VAS)	0.0/10(0.0)	n/a	5.5/10(2.0)	0.28	4.9/10(1.0)
LEFS (x/80)	80.0/80 (0.0)	n/a	57.4/80(15.4)	0.30	61.8/80(8.0
Duration of PFP (months)	n/a	n/a	25.8(20.1)	0.018*	48.6(26.6)

Table 2: Peak variables (SD) of interest during running. *signifies p>0.05. CPD= contralateral pelvic drop, HADD= hip adduction, HIR= hip internal rotation, KADD= knee adduction, external KADD moment= external knee adduction moment. Please note that a negative value for CPD indicates a contralateral pelvis that is depressed.

Run	Controls	=> p <=	Males PFP	=> p <=	Females PFP
CPD (deg)	-3.9(2.3)	0.002*	-6.5(2.2)	0.192	-7.7(2.2)
HADD (deg)	11.9(3.0)	0.394	12.9(3.4)	0.000*	19.2(3.0)
HIR (deg)	6.0(3.8)	0.557	6.9(4.6)	0.176	9.0(4.8)
Knee Ext (deg)	-48.1(2.8)	0.77	-47.7(4.8)	0.13	-50.2(4.8)
KADD (deg)	2.7(3.2)	0.029*	5.7(1.0)	0.018*	2.2(4.0)
External KADD moment (N*m/kg*m)	0.543(0.162)	0.041*	0.688(0.240)	0.342	0.613(0.227)
Femoral Adduction (deg)	5.6(1.8)	0.096	4.4(2.4)	0.000*	7.3(1.5)
Tibial Adduction (deg)	4.9(1.8)	0.05*	6.5(2.9)	0.09	4.9(2.6)
TMA (deg)	7.7(2.4)	0.89	7.8(2.4)	0.21	6.5(2.0)

Table 3: Variables of interest (SD) for the single leg squat mechanics, indexed to peak knee flexion for each respective runner. *signifies p>0.05. CPD= contralateral pelvic drop, HADD= hip adduction, HIR= hip internal rotation, KADD= knee adduction, external KADD moment= external knee adduction moment. Please note that a positive value for CPD indicates a contralateral pelvis that is elevated.

Single leg squat	M-CON	=> p <=	M-PFP	=> p <=	F-PFP
CPD (deg)	2.9(2.8)	0.136	1.3(3.8)	0.733	1.7(3.3)
HADD (deg)	6.2(3.7)	0.959	6.2(4.4)	0.007*	10.4(4.2)
HIR (deg)	5.7(5.1)	0.972	5.8(5.4)	0.745	5.2(5.5)
KADD (deg)	2.4(4.3)	0.021*	6.0(4.6)	0.000*	-1.6(4.8)
External KADD moment (N*m/kg*m)	0.192(0.082)	0.294	0.220(0.073)	0.165	0.184(0.079)
Femoral Adduction (deg)	9.0(2.3)	0.46	8.4(2.8)	0.001*	11.4(2.1)
Tibial Adduction (deg)	5.2(2.0)	0.09	6.3(2.0)	0.004*	3.8(2.7)