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Increased hip adduction during running is associated with patellofemoral pain and differs between males and females: A case-control study

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ABSTRACT

Patellofemoral pain is common amongst recreational runners and associated with altered running kinematics. However, it is currently unclear how sex may influence kinematic differences previously reported in runners with patellofemoral pain. This case-control study aimed to evaluate lower limb kinematics in males and females with and without patellofemoral pain during running. Lower limb 3D kinematics were assessed in 20 runners with patellofemoral pain (11 females, 9 males) and 20 asymptomatic runners (11 females, 9 males) during a 3 km treadmill run. Variables of interest included peak hip adduction, internal rotation and flexion angles; and peak knee flexion angle, given their previously reported association with patellofemoral pain. Age, height, mass, weekly run distance and step rate were not significantly different between groups. Mixed-sex runners with patellofemoral pain were found to run with a significantly greater peak hip adduction angle (mean difference = 4.9°, d = 0.91, 95% CI 1.4–8.2, p = 0.01) when compared to matched controls, but analyses for all other kinematic variables were non-significant. Females with patellofemoral pain ran with a significantly greater peak hip adduction angle compared to female controls (mean difference = 6.6°, p = 0.02, F = 3.41, 95% CI 0.4–12.8). Analyses for all other kinematic variables between groups (males and females with/without PFP) were non-significant. Differences in peak hip adduction between those with and without patellofemoral pain during running appear to be driven by females. This potentially highlights different kinematic treatment targets between males and females. Future research is encouraged to report lower limb kinematic variables in runners with patellofemoral pain separately for males and females.

1. Introduction

Patellofemoral pain (PFP) is described as either retropatellar or peripatellar pain of atraumatic onset, associated with knee joint loading into flexion (Crossley et al., 2016). Running is a common aggravating factor, with incidence reported to range from as low as 4% throughout a two year period (Noehren et al., 2013), to as high as 21% during a ten week ‘start to run’ programme (Thijs et al., 2011). A recent systematic review and meta-analysis identified no risk factors from pooled prospective data for the development of PFP in a recreational running population (Neal et al., 2018a).

Whilst there is a paucity of prospective research investigating risk factors for PFP in running populations, female recreational runners have been reported to be at an increased risk of developing PFP in the presence of a high peak hip adduction angle (Noehren et al., 2013). Additionally, runners with persistent PFP have been reported to run with increased peak hip adduction and internal rotation angles compared to asymptomatic controls (Fox et al., 2018; Noehren et al., 2012a; Noehren et al., 2012b; Willy et al., 2012a). Whilst there are literature to the contrary (Dierks et al., 2011; Esculier et al., 2015), a recent meta-analysis identified moderate to strong cross-sectional associations between PFP and altered pelvic and hip kinematics when all available data are

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pooled (Neal et al., 2016). It is thought that these kinematic variations may contribute to the development and persistence of PFP by way of increasing patellofemoral joint stress, and thus provide treatment targets when using interventions such as gait retraining (Noehren et al., 2011; Willy et al., 2012b).

Recreational runners with PFP have been reported to demonstrate a reduced stance phase hip flexion angle when compared to matched controls (Bazett-Jones et al., 2013). In addition, an increased peak knee flexion angle has been reported to increase patellofemoral joint stress (Lenhart et al., 2014), with a reduced peak knee flexion angle also correlating positively with symptom reduction after step-rate retraining (Neal et al., 2018b). As these sagittal plane variables are associated with PFP persistence and may present potential treatment targets, their further investigation was warranted given the lower volume of work to date in comparison to variables in the frontal and transverse planes.

A higher prevalence of PFP is reported amongst females (Boling et al., 2010). However, despite the breadth of literature evaluating the kinematics of runners with PFP, current understanding of the influence of sex on running kinematics in those with PFP is poor. Multiple studies have evaluated only females with PFP (Noehren et al., 2012a; Noehren et al., 2012b), while others have evaluated mixed-sex PFP cohorts with no sub-analysis of the individual sexes (Bazett-Jones et al., 2013; Dierks et al., 2008; Esculier et al., 2015). This is problematic, as asymptomatic females are reported to demonstrate different kinematic (Chumanov et al., 2008) and kinetic (Sinclair and Selfe, 2015) profiles during running in comparison to males.

One previous study evaluated kinematic differences between males and females with PFP during running (Willy et al., 2012a), reporting that females with PFP demonstrate a greater peak hip adduction angle compared to both males with PFP and male controls. In contrast, males with PFP were reported to run with a greater peak knee adduction angle when compared to both females with PFP and male controls. Limitations of this study include use of a fixed speed (3.35 m/sec), which may result in different findings to when running at a self-selected speed (Schache et al., 2011; Vincent et al., 2014); and the lack of a female control group. Improving understanding of how kinematic associations with PFP may differ between sexes is important to guide the development of more tailored interventions for this often persistent condition (Lankhorst et al., 2016).

This case-control study aimed to evaluate treadmill-running kinematics at self-selected speeds in a mixed sex cohort of runners with and without PFP. A secondary aim was to further analyse kinematic data when these cohorts were divided into males and females with and without PFP, to investigate potential kinematic differences between the sexes. It was hypothesised that runners with PFP would demonstrate an increased peak hip adduction angle in comparison to matched controls, with greater increases observed amongst females with PFP.

2. Methods

2.1. Participants

The Queen Mary Ethics of Research Committee granted ethical approval for this study (QMREC2014/63) and all participants provided written informed consent prior to participation. A convenience sample of participants with and without PFP was sought from local sports medicine clinics and running clubs respectively.

An a priori sample size calculation for one-way, fixed-effects ANOVA was conducted, with peak hip adduction angle as the primary dependent variable. Using data from previous work, (males with PFP 12.9° [±3.4], females with PFP 19.2° [±3.0], male controls 11.9° [±3.0]), (Willy et al., 2012a) five participants were required to determine the difference between these three groups, achieving $\alpha = 5\%$ and $\beta = 0.80$, with an effect size (f) of 3.2 (calculated using G*Power 3.1.9.3, Heinrich-Heine University, Germany). We therefore recruited 20 participants per group defined either by sex or presence of PFP, allowing for five participants per dependent variable to be investigated.

20 runners with PFP (11 females, 9 males) and 20 asymptomatic runners (11 females, 9 males) were recruited (see Table 1). To be included in the PFP group, participants were required to have retropatellar or peripatellar pain for at least the past three months, with their worst pain (most significant) rated at a minimum of three (out of a maximum of 10) using a numerical rating scale (NRS). An average pain (day to day) score using the NRS was also recorded. Symptoms were required to be present during running and one other activity described by the most recent PFP consensus document (Crossley et al., 2016). Participants with patellofemoral instability, tibiofemoral pathology or previous lower limb surgery were excluded. To be included in the control group, participants were required to be free of running-related injury for a minimum of three months and have no previous history of PFP. All participants were of either sex, currently or recently running a minimum of 10 km/week and aged between 18 and 45 years.

2.2. Experimental protocol

Participants were required to present to the Human Performance Laboratory at Queen Mary University of London. Data pertaining to one limb, rather than two, was entered into the analysis to reduce type I error potential (Menz, 2005). For participants with bilateral symptoms, the limb that rated the highest on the worst pain numerical rating scale was included. For participants with equivalent symptoms, or for the control participants, the dominant limb (defined as the limb that would be used to kick a ball) was included (Willy et al., 2012b). Participants in the PFP group also completed the Kujala Scale (Kujala et al., 1993), a 13-question appraisal of subjective function in those with PFP, with a score of 100 representing no symptoms and a score of zero indicating complete disability.

2.3. Kinematic measures

Kinematic data were collected during running using a four-camera, infrared motion analysis system (CX-1, Codamotion, Charnwood Dynamics Limited, Leicestershire, UK) (Lack et al., 2014). 24 infrared markers, consisting of eight individual markers and four rigid clusters of four markers, were placed on standard pelvic and lower limb anatomical landmarks using the CAST protocol by the primary investigator (BN) (Cappello et al., 1997). Unpublished laboratory data for the primary investigator (BN) have previously identified moderate to excellent intra-rater reliability (ICC 0.62–0.93), with respect to positioning of kinematic markers in three-dimensional space. Rigid clusters were applied using adjustable elastic straps and were secured with cohesive self-adherent bandage and individual markers were applied using double-sided adhesive tape and secured with transparent surgical tape. Virtual markers were also identified on the femoral epicondyles and the ankle malleoli, to allow for the calculation of relevant joint centers during an upright standing calibration trial. The knee joint centre was estimated as the mid-point between the femoral epicondyle markers and the hip joint centre was estimated as a projection within the pelvis frame using previously described methods (Bell et al., 1990). Joint centre calculation did not differ between male and female participants.

Table 1
Participant characteristics.

Variable	Male PFP Mean (SD)	Male Control Mean (SD)	Female PFP Mean (SD)	Female Control Mean (SD)
Age (Years)	31.8 (7.6)	28.7 (4.4)	29.4 (4.3)	32.4 (4.7)
Height (cm)	179.8 (5.3)	177.5 (6.8)	153.9 (6.4)	167.1 (4.8)
Mass (kg)	74.2 (7.9)	73.2 (11.9)	56.8 (5.8)	59.5 (6.3)
Average run volume (km)	18.1 (7.3)	15.8 (9.7)	16.3 (10.5)	23.0 (13.0)
Step rate (SPM)	164.2 (7.3)	166.7 (8.7)	151.2 (3.9)	167.5 (6.5)
Symptom duration (Months)	73.3 (66.2)	N/A	37.9 (3.2)	N/A
Kujala scale	89.2 (5.1)	N/A	79.1 (7.9)	N/A
Average NRS	3.0 (1.8)	N/A	3.2 (1.3)	N/A
Worst NRS	7.0 (1.8)	N/A	6.0 (1.1)	N/A

Key: SD = standard deviation; SPM = steps per minute; NRS = numerical rating scale; N/A = not applicable.

Participants were required to run in their usual running shoes and at their typical 'steady state' running speed on the laboratory treadmill (Kistler Gaitway, Kistler Group, Winterthur, Switzerland). Participants were given approximately six minutes to acclimate their running gait to the treadmill condition, previously reported to allow for representation of a participant's typical running gait (Lavcanska et al., 2005). Participants ran for a total of three kilometers (km), with 10 s of data sampled at 200 Hz collected at 0.8/1.8/2.8 km. Distance, as opposed to time, was chosen to act as a constant measure across a cohort of participants running at different speeds.

To increase the reliability of gait analysis, multiple data collections were completed. (Monaghan et al., 2007) Specifically, a peak kinematic outcome for all dependent variables was determined for each individual stance phase, with an average then determined for each 10 s of data collection, subsequently mean pooled across the three individual data collections described above. (Neal et al., 2018b) Participants in the PFP group were given the option to cease data collection if their symptoms increased to four or greater on the NRS. Variables of interest included peak hip adduction, internal rotation and flexion angles and peak knee flexion angle, based on between group differences (PFP compared to control) identified in our recent meta-analysis. (Neal et al., 2016)

2.4. Data analysis

Data were analysed offline using a customised Matlab program (version 2015, Mathworks, Natick, Massachussets, USA). Initial foot contact and toe off were identified using the calcaneal tuberosity marker and the metatarsal head marker in the vertical (Z) axis. Consistent with previously described methods, initial foot contact was defined as the point at which the calcaneal tuberosity marker ceased its descent in the vertical axis. (Fellin et al., 2010; Zeni et al., 2008) Toe off was identified by determining peak acceleration of the fifth metatarsal marker relative to the calcaneal tuberosity marker. (Fellin et al., 2010; Schache et al., 2001) These methods have previously been reported to have low absolute errors. (Fellin et al., 2010) All kinematic data were aligned to initial foot contact, interpolated and normalised to percentage of stride cycle (0% = initial contact, 100% = terminal stance).

2.5. Statistical analysis

All statistical testing were performed offline using SPSS (version 22 for MacOS, IBM, New York, USA). Two-tailed, independent samples t-tests were used to determine statistical differences between pairs of groups (PFP versus control). One-way analysis of variance (ANOVA) with four sub-groups defined by sex and symptoms was conducted, with a Tukey's post-hoc test, which does not require statistical correction for multiple comparisons. Statistical significance of data were set at $\alpha \leq 0.05$, with a trend defined as $\alpha \leq 0.10$. Cohen's *d* was also calculated to determine the effect size of all identified inter-group differences, alongside the reporting of mean differences and 95% confidence intervals (CI). Cohen's *d* was interpreted as small (≤0.2), medium (>0.5) and large (>0.8) respectively (Sullivan and Feinn, 2012). Greatest individual absolute between day difference (GBDD) data (without a marker placement device) from previous work (Noehren et al., 2010) were used to determine the clinical relevance of identified kinematic differences.

3. Results

3.1. Participant characteristics

Analyses of all characteristics between groups were non-significant and are detailed in Table 1 (P = 0.23–0.59). Participants in the PFP group demonstrated a prolonged duration of pain (55.8 [±51.6] months), but only a mild impairment in function, reflected by a mean Kujala scale score of 87.6 (±6.8).

3.2. PFP versus control (mixed-sex)

The mixed-sex PFP cohort ran with a significantly greater peak hip adduction angle (mean difference = 4.9°, P = 0.01, d = 0.91, 95% CI 1.4–8.2) when compared to the control group (see Fig. 1). No significant differences were identified for any other variable (see Table 2).

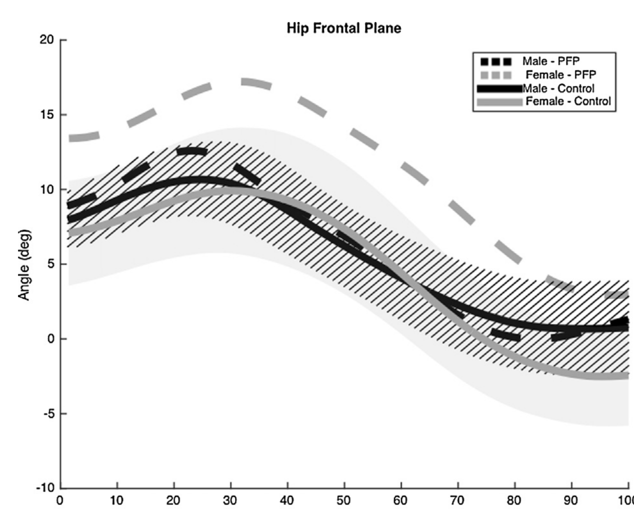

Fig. 1. Graph depicting pooled mean hip adduction for all four groups during running stance phase. Solid and dashed error bars reflect 95% confidence intervals for female and male control subjects respectively.

Table 2
Comparison between participants with PFP and matched controls.

Variable	PFP Mean (SD)	Controls Mean (SD)	Mean Difference	*P*	*d*	95% CI
KFLEX	37.7° (5.5)	36.6° (5.7)	1.1°	0.54	0.19	−2.5 to 4.7
HFLEX	26.0° (7.4)	23.8° (8.2)	2.2°	0.38	0.28	−2.8 to 7.2
HADD	16.5° (4.5)	11.6° (6.2)	4.9° (+)	0.01*	0.92	1.4 to 8.2
HIR	9.4° (7.6)	7.3° (7.0)	2.1°	0.37	0.28	−2.6 to 6.8

Key: SD = standard deviation; KFLEX = peak knee flexion; HFLEX = peak hip flexion; HADD = peak hip adduction; HIR = peak hip internal rotation; CI = confidence interval; * =indicates significance; (+) mean difference exceeds GBDD.

3.3. Sub-group analysis

Females with PFP ran with a significantly greater peak hip adduction angle compared to female controls (mean difference = 6.6°, $P = 0.02$, F = 3.41, 95% CI 0.4 to 12.8), with a trend towards female runners having a significantly greater peak hip adduction angle when compared to male controls (mean difference = 6.3°, $P = 0.06$, F = 3.41, 95% CI −0.3 to 12.8) (see Fig. 1). No significant differences were identified for any other variable. Full details can be found in Table 3.

4. Discussion

Our findings indicate a greater peak hip adduction angle during running in the PFP group, compared to matched controls when mixed sex comparisons are made. However, this difference appears to be influenced by participant sex, with a greater peak hip adduction angle observed in female runners with PFP compared to female controls, but with no differences identified between males with and without PFP.

4.1. Frontal plane hip kinematics

Findings of a greater peak hip adduction angle in this mixed-sex cohort of runners with PFP compared to matched controls are consistent with Fox et al, who recently reported greater frontal plane hip motion during running in their chronic PFP cohort (Fox et al., 2018). However, they conflict with other mixed-sex studies (Bazett-Jones et al., 2013; Dierks et al., 2011; Esculier et al., 2015), which reported no differences in peak hip adduction angle when comparing runners with PFP to asymptomatic runners.

Fox et al did not report a difference in peak hip adduction angle for their acute PFP cohort (defined as the presence of PFP for less than one month), compared to matched controls (Fox et al., 2018). As Dierks et al and Bazett-Jones et al used similar inclusion criteria (minimum symptom duration one to two months) (Bazett-Jones et al., 2013; Dierks et al., 2011) and did not report on symptom duration, it could be that symptom duration explains the conflicting kinematic outcomes. However, Esculier et al included participants with more prolonged PFP symptoms (mean duration 38.1 [±45.5] months) (Esculier et al., 2015), which is comparable to the symptom duration observed in participants from this study (mean duration 55.8 [±51.6] months) and Fox et al (mean duration 32.2 [±35.5] months) (Fox et al., 2018). It is therefore more likely that this conflict can simply be explained by the accepted heterogeneity of PFP as a condition (Powers et al., 2017).

4.1.1. Frontal plane hip kinematics: The influence of sex

Our findings indicate a greater peak hip adduction angle in females with PFP compared to female controls. These data are in agreement with the three previous case-control studies comparing females with PFP to female controls (Noehren et al., 2012a; Noehren et al., 2012b; Willson and Davis, 2008), all of which reported a higher peak hip adduction angle during running in the PFP cohorts.

Esculier et al reported no differences in peak hip adduction angle between groups for their mixed-sex comparison (Esculier et al., 2015). They did however report a significant difference in peak hip adduction angle between participants with and without PFP when performing a sub-analysis for female participants at the toe-off phase of gait (mean difference 5.4°) (Esculier et al., 2015). This is consistent with the findings of our study and given the large mean differences in peak hip adduction angle between females with PFP and both female (6.6°) and male (6.3°) controls, it is suggested that these female PFP data may be resulting in the significant difference for the pooled mixed-sex outcome.

Consistent with our findings, Willy et al reported that females with PFP ran with a greater peak hip adduction angle compared to male controls (Willy et al., 2012a). However, contrary to our findings, they also reported that their female PFP cohort ran with a significantly greater hip adduction angle compared with their male PFP cohort. As the mean difference from our data is above the GBDD for hip adduction when comparing these groups (3.5° greater in the female PFP group) (Noehren et al., 2010), it is likely that our smaller sample size (n = 11 compared to n = 18) accounts for the lack of statistical significance in our findings. Considering sex specific differences identified in our current, and previous studies, future studies evaluating running kinematics are advised

Table 3
Sub-analyses for the individual sexes when comparing between participants with and without PFP.

	Female Controls (n = 11) Mean (SD)	→*P*←	Mean difference	Female PFP (n = 11) Mean (SD)	→*P*←	Mean Difference	Male PFP (n = 9) Mean (SD)	→*P*←	Mean difference	Male Controls (n = 9) Mean (SD)
KFLEX	35.3° (4.8)	0.74	2.4°	37.7° (6.3)	1.00	0.0°	37.7° (5.0)	0.99	0.5°	38.2° (6.6)
HFLEX	23.4° (9.7)	1.00	0.3°	23.1° (7.7)	0.26	6.4°	29.5° (5.6)	0.46	5.3°	24.2° (6.5)
HADD	11.5° (7.5)	0.03*	6.6° (+)	18.1° (3.8)	0.47	3.5° (+)	14.6° (4.7)	0.70	2.8°	11.8° (4.5)
HIR	9.6° (5.3)	0.99	0.6°	10.2° (7.3)	0.94	1.8°	8.4° (8.3)	0.67	3.9°	4.5° (8.2)

Key: SD = standard deviation; KFLEX = peak knee flexion; HFLEX = peak hip flexion; HADD = peak hip adduction; HIR = peak hip internal rotation; * =indicates significance; (+) mean difference exceeds GBDD.

to report data for males and females separately, irrespective of study design.

4.2. Sagittal plane kinematics

A previous mixed-sex study reported a significantly lower peak hip flexion angle in runners with PFP (30.4°) compared to controls (35.8°) (Bazett-Jones et al., 2013), which was not observed in this mixed-sex cohort. However, whilst not statistically significant, a lower peak hip flexion angle was observed in female runners with PFP (23.1°), compared to male runners with PFP (29.5°) in this study. Bazett-Jones et al hypothesized that an increase in peak hip flexion angle may be an attempt to compensate for weakness of the hip extensor muscles (Bazett-Jones et al., 2013), which have a mechanical advantage in positions of greater hip flexion. However, there is a greater breadth of literature reporting lower isometric hip extensor strength in females with PFP (Rathleff et al., 2014) and muscle strength and running kinematics have been previously reported to not be associated (Hannigan et al., 2017), bringing this hypothesis into question. Future studies are encouraged to further investigate the influence of sagittal plane hip kinematics on PFP.

Despite previous studies reporting that peak knee flexion angle correlates positively with patellofemoral joint stress (increased flexion = increased stress), no increase in peak knee flexion angle was observed in our PFP group. This is in agreement with the previous study of Wirtz et al, who reported no increases in patellofemoral joint stress when comparing female runners to matched controls (Wirtz et al., 2012). Individuals with PFP have previously been reported to perform stair ambulation with reduced knee flexion, thought to be in attempt to control pain by mediating patellofemoral joint stress (Crossley et al., 2004). The increased peak hip flexion angle observed in the males with PFP in this study may reflect kinesophobia (a reluctance to or fear of flexing the knee joint), a phenomenon previously observed in individuals with PFP (de Oliveira Silva et al., 2019), though it is unclear why such an adaptation would not be observed in the female group. Further investigation of sagittal plane hip and knee mechanics and their influence on PFP during running is encouraged.

4.3. Individual kinematic responses

Some participants from both sexes do demonstrate individual kinematic patterns that are in contrast to the mean pooled data (see Fig. 2). In the male subgroup, there were two PFP participants with a peak hip adduction angle below the pooled mean of the control group (9.8° and 6.9° respectively), and three control participants with a peak hip adduction angle above the pooled mean of the PFP group (15.4°, 15.5° and 16.4° respectively). However, in the female subgroup, there were no PFP participants with a peak hip adduction angle below the pooled mean of the control group and three control participants with a peak hip adduction angle above the pooled mean of the PFP group (19.2°, 19.6° and 21.6° respectively). Whilst this further confirms an association between an increased peak hip adduction angle during running and PFP, especially in females, such an increase was not observed in all participants.

4.4. Kinematic treatment targets

In previous observational case series, gait-retraining interventions to reduce peak hip adduction angle during running have been reported to reduce pain and improve function in females with PFP (Noehren et al., 2011; Willy et al., 2012b). The mean reduction in peak hip adduction angle from these studies was 5°, comparable to the magnitude of difference between the females with PFP and the female controls (6.6°) in this study. When considered alongside the fact that an increased peak hip adduction angle was not associated with PFP in male runners in these and other studies data (Willy et al., 2012a), it is suggested that gait-retraining interventions to reduce peak hip adduction angle may only applicable to female runners with PFP. However, an absence of benefit in males with PFP would need to be observed through further research to confirm this.

4.5. Limitations and future directions

Findings from this study should be interpreted within the context of its limitations. The retrospective, case-control design does not allow for the interpretation of causality and it may be that the observed kinematics are simply adaptations to persistent pain rather than the primary driver of symptoms (Lack et al., 2018). Whilst there are some data to support the notion that altered hip kinematics may increase the risk of future PFP development in female runners (Noehren et al., 2013), there remains a dearth of prospective literature. Further research is needed to determine if males and females might have different running kinematic risk profiles for the development of PFP.

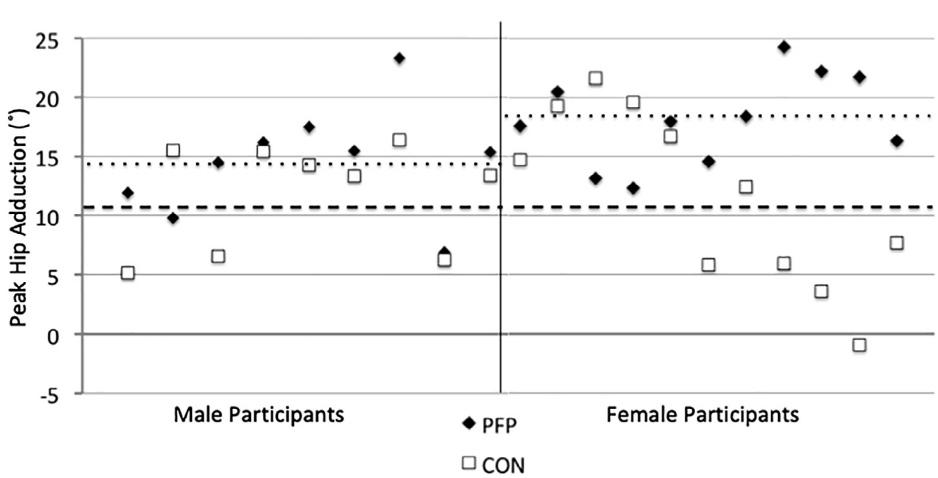

Fig. 2. Individual peak hip adduction data points for participants with and without PFP, with each sex presented individually. The dotted line represents the pooled mean of the PFP group and the dashed line represents the pooled mean of the control group (CON).

Treadmill running gait, which was evaluated in this study, may not fully reflect kinematics of over ground running. However, it has been reported that hip and knee kinematics (Fellin et al., 2010), as well as peak and rate of patellofemoral joint stress (Willy et al., 2016) are not significantly different when comparing treadmill with over ground running in asymptomatic populations. As participants were also given approximately six minutes to acclimate their running gait to the treadmill condition (Lavcanska et al., 2005), appropriate steps have been taken to ensure that the reported results are representative of a participant's typical running gait.

Kinematic data were collected at specific points during a 3 km run before subsequently being pooled. There is therefore the potential for fatigue to have influenced the kinematic outcomes in this study, which we attempted to mitigate by instructing participants to self-select their own 'steady state' running speed. This should have prevented participants from reaching the levels of fatigue previously reported to significantly alter running kinematics (Bazett-Jones et al., 2013; Dierks et al., 2011), though we did not apply any metric to measure any potential fatigue.

5. Conclusion

Our findings indicate runners with PFP have a significantly greater peak hip adduction angle when compared to matched controls. This finding appears to be influenced by sex, as females, but not males, were found to have a significantly greater peak hip adduction angle when compared to sex matched controls. These differences between sexes in kinematic profiles may highlight the need for different treatment targets in males and females. Future research is encouraged to report lower limb kinematic variables in runners with PFP separately for males and females.

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None to declare. This study was unfunded.

Declaration of Competing Interest

The authors declare that they have no conflicts of interest in relation to this study.

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