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Lower Extremity Kinetics and Kinematics in Runners with Patellofemoral Pain: A Retrospective Case–Control Study Using Musculoskeletal Simulation

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Abstract: Patellofemoral pain (PFP) is a common atraumatic knee pathology in runners, with a complex multifactorial aetiology influenced by sex differences. This retrospective case–control study therefore aimed to evaluate lower limb kinetics and kinematics in symptomatic and control male and female runners using musculoskeletal simulation. Lower extremity biomechanics were assessed in 40 runners with PFP (15 females and 25 males) and 40 controls (15 females and 25 males), whilst running at a self-selected velocity. Lower extremity biomechanics were explored using a musculoskeletal simulation approach. Four intergroup comparisons—(1) overall PFP vs. control; (2) male PFP vs. male control; (3) female PFP vs. female control; and (4) male PFP vs. female PFP—were undertaken using linear mixed models. The overall (stress per mile: PFP = 1047.49 and control = 812.93) and female (peak stress: PFP = 13.07 KPa/BW and control = 10.82 KPa/BW) comparisons showed increased patellofemoral joint stress indices in PFP runners. A significantly lower strike index was also shown in PFP runners in the overall (PFP = 17.75% and control = 33.57%) and female analyses (PFP = 15.49% and control = 40.20%), revealing a midfoot strike in control, and a rearfoot pattern in PFP runners. Peak rearfoot eversion and contralateral pelvic drop range of motion (ROM) were shown to be greater in PFP runners in the overall (eversion: PFP = −8.15° and control = −15.09°/pelvic drop ROM: PFP = 3.64° and control = 1.88°), male (eversion: PFP = −8.05° and control = −14.69°/pelvic drop ROM: PFP = 3.16° and control = 1.77°) and female (eversion: PFP = 8.28° and control = −15.75°/pelvic drop ROM: PFP = 3.64° and control = 1.88°) PFP runners, whilst female PFP runners (11.30°) exhibited a significantly larger peak hip adduction compared to PFP males (7.62°). The findings from this investigation highlight biomechanical differences between control and PFP runners, as well as demonstrating distinctions in PFP presentation for many parameters between sexes, highlighting potential risk factors for PFP that may be addressed through focused intervention modalities, and also the need, where appropriate, for sex-specific targeted treatment approaches.

Keywords: patellofemoral pain; running; musculoskeletal simulation; anterior knee pain; kinematics

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1. Introduction

Both recreational and competitive distance running are associated with a plethora of physiological benefits [1]. However, despite the physical improvements caused by running, it is also linked with a very high rate of overuse injuries [2,3]. Patellofemoral pain (PFP) is a common atraumatic knee pathology that typically manifests as retropatellar or peripatellar pain and inflammation, aggravated by activities that frequently load the joint [4]. PFP has an incidence rate as high as 21% in runners [5], with a much larger prevalence in females [6]. The long-term prognosis is poor, with 71–91% of patients experiencing symptoms 20 years after diagnosis [7]. PFP symptoms may later present with radiographic evidence of osteoarthritis at this joint [8], and pain symptoms force many to reduce or even end their running training [9], causing many to develop associated psychological disorders [10].

The lack of treatment efficacy is attributed to the multifactorial nature and complex aetiology of PFP, which makes the identification of modifiable risk factors problematic [11]. Given the high incidence of PFP in runners [5], an enhanced comprehension of the parameters linked to PFP's aetiology and its distinct incidence in differing populations is essential in order to prevent symptoms and improve management. Recent prospective pooled systematic reviews and meta-analyses have shown physiological indices of quadriceps weakness and hip abduction strength to be risk factors for PFP in military and adolescent populations, although no identifiable risk factors were evident in runners [12].

There is a lack of prospective investigations exploring the biomechanical mechanisms linked to the aetiology of PFP in runners [4]. Noehren et al. [13] showed that female runners were at an increased risk of developing PFP in the presence of a statistically greater maximum hip adduction angle. Furthermore, in relation to asymptomatic controls, Fox et al. [14] showed that PFP runners exhibited increased peak hip adduction, hip transverse plane range of motion (ROM), peak knee flexion, peak knee abduction, and peak dorsiflexion. Noehren et al. [15,16] revealed that in female PFP runners, increased hip adduction, hip internal rotation, and tibial internal rotation were evident compared to controls. Esculier et al. [17] showed that runners with PFP exhibited higher hip adduction at toe-off, lower hip adduction ROM during late-stance, and longer soleus activation. Conversely, Dierks et al. [18] showed that runners with PFP demonstrated reduced peak knee flexion, peak hip adduction, eversion ROM, peak knee flexion velocity, peak hip adduction velocity, and peak hip internal rotation velocity compared with controls. Finally, Willson and Davis [19] revealed that females with PFP demonstrated greater hip adduction and contralateral pelvic drop compared to asymptomatic runners. Neal et al. [12] proposed that these kinematic variations contribute to the development and persistence of PFP by way of increased patellofemoral joint stress, although patellofemoral joint loading has not yet been explored in runners with PFP in relation to asymptomatic controls.

Although previous analyses have explored the biomechanics of running in those with PFP compared to healthy controls, the majority utilized only female runners or a mixed-sex sample, without considering of the effects of sex. As such, the effects of sex on the biomechanics of running in those with PFP are poorly understood [12]. Willy et al. [20] compared the biomechanics of running in male and female runners with PFP, and showed that females exhibited greater peak hip adduction compared to both males with PFP and male controls, whereas males with PFP ran with a greater peak knee adduction compared to symptomatic females and male controls. A drawback of this investigation was the lack of a female control group, and Neal et al. [4] undertook the only investigation examining male and female runners with PFP in relation to asymptomatic controls of both sexes. Mixed-sex comparisons showed that PFP runners exhibited greater peak hip adduction compared to controls. Females with PFP demonstrated significantly greater peak hip adduction compared to controls, but there were no differences between males with PFP and male controls.

Previous analyses concerning the biomechanical differences between runners with PFP and asymptomatic controls have examined only joint kinematics, ground reaction forces, and surface electromyography. Significant advances have been made in musculoskeletal simulation models [21], leading to the development of bespoke software allowing skeletal muscle forces to be simulated during movement and utilized as inputs to calculate lower extremity joint reaction forces [22]. Such approaches have been used extensively in running, but only one study has explored differences between those with PFP and healthy controls. Besier et al. [23] showed that medial gastrocnemius forces were significantly greater in PFP runners, which they speculated may cause greater joint contact loads in comparison to pain-free runners, although joint loading indices were not undertaken in this investigation. With the high incidence of PFP in runners [5], associated with a poor long-term prognosis [7], further investigation is warranted in order to better understand the biomechanical variables associated with PFP and the increased incidence of this pathology in female runners, so as to enhance the quality of future evidence-based preventative strategies for both sexes.

This investigation, via a retrospective case–control study design, aimed firstly to evaluate the biomechanics of running in a pooled-sex sample of runners with and without PFP using a musculoskeletal simulation-based approach. Secondly, using the same experimental approach, this investigation sought to explore differences between runners with PFP and asymptomatic controls, when these cohorts were divided into subset comparisons of males and females with and without PFP, in order to investigate distinctions in PFP presentation between the sexes.

2. Materials and Methods

2.1. Participants

The University of Central Lancashire granted ethical approval for this study (STEMH 424), and all participants provided written informed consent prior to participation, in accordance with the Declaration of Helsinki. Runners with and without PFP were recruited from local sports physiotherapy clinics and running clubs/teams. An a priori sample size calculation for independent group comparisons between sexes was undertaken, using the formulae outlined by Rosner [24]. The peak patellofemoral joint stress was adopted as the primary dependent variable. Using data from our previous work, (males with PFP: 13.10 ± 3.05 megapascals (MPa) [25]; male controls: 10.80 MPa ± 3.04 [26]; females with PFP: 10.60 MPa ± 1.20 [27]; and female controls: 9.27 MPa ± 1.36 [28]), it was determined that in order to achieve α = 5% and β = 0.80, 15 female and 25 male runners were required in both the control and PFP groups.

Specific diagnosis of PFP was made in accordance with previous guidelines [29]; it was also required that runners had experienced patellofemoral symptoms for a minimum of 3 months that were exacerbated by running or other activities. Participants with any other knee/lower limb pathology or previous lower limb surgery were excluded. For inclusion in the control group, it was necessary for runners to be free of running-related injury for at least three months, and to have no prior history of anterior knee pain. Both groups were composed of participants of either sex, commonly running at least 10 km per week, and aged between 18 and 45 years [4].

2.2. Procedures

Participants presented to the Biomechanics Laboratory at the University of Central Lancashire. In runners who experienced bilateral PFP, the limb that exhibited the greater symptoms was included [4]; for the control participants, the dominant limb (defined as the limb that would be used to kick a football) was utilized [20]. Participants in the PFP group completed the Knee Osteoarthritis Outcome Score Patellofemoral subscale (KOOS-PF); this scale is scored from 0 to 100, with 100 representing no disability and 0 representing maximum disability [30].

Participants ran across the Biomechanics Laboratory, striking an embedded piezoelectric force platform (Kistler Instruments Ltd., Winterthur, Switzerland)—which sampled at 1000 Hz—with their appropriate foot. Participants were required to run in their usual running shoes and at their own typical/self-selected running speed. The stance phase was delineated as the duration over which 20 N or greater of vertical ground reaction force (GRF) was applied to the force platform [31]. Runners completed five successful trials, with a successful trial being defined as one where the foot made full contact with the force platform, and with no evidence of gait modifications due to the experimental conditions. Kinematic and GRF data were synchronously collected. Kinematic data were captured at 250 Hz via an eight-camera motion analysis system (Qualisys Medical AB, Gothenburg, Sweden). Dynamic calibration of the motion capture system was performed before each data collection session.

Body segments were modelled in 6 degrees of freedom using the calibrated anatomical systems technique [32]. To define the anatomical frames of the thorax, pelvis, thighs, shanks, and feet, retroreflective markers were placed at the 7th cervical vertebrae (C7), 12th thoracic vertebrae (T12), and xiphoid process landmarks, and also positioned bilaterally onto the acromion process, iliac crest, anterior superior iliac spine (ASIS), posterior super iliac spine (PSIS), medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanter, calcaneus, and 1st and 5th metatarsals (Figure 1a). Intra-rater reliability for the researcher responsible for positioning of the aforementioned anatomical markers has been shown to be excellent [33]. The centres of the ankle and knee joints were delineated as the midpoints between the malleoli and the femoral epicondyle markers [34,35]. The hip joint centre was determined using a regression equation that uses the positions of the ASIS markers [36]. Carbon-fibre tracking clusters comprising four non-linear retroreflective markers were positioned onto the thigh and shank segments. In addition, the foot segments were tracked via the calcaneus, first metatarsal, and fifth metatarsal, the pelvic segment was tracked using the PSIS and ASIS markers, and the thorax segment was tracked using the T12, C7, and xiphoid markers. Static calibration trials were carried out, allowing for the anatomical markers to be referenced in relation to the tracking markers/clusters. The Z (transverse) axis was oriented vertically from the distal segment end to the proximal segment end. The Y (coronal) axis was oriented in the segment from posterior to anterior. Finally, the X (sagittal) axis orientation was determined using the right-hand rule, and was oriented from medial to lateral (Figure 1b).

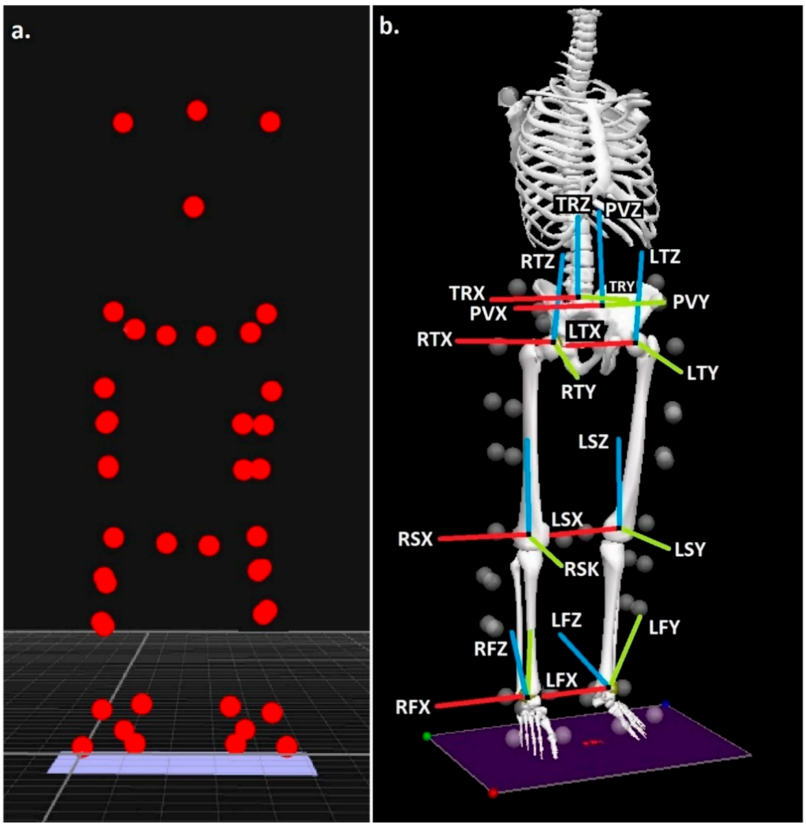

Figure 1. (**a**) Experimental marker locations and (**b**) trunk, pelvis, thigh, shank, and foot segments, with segment co-ordinate system axes (R = right and L = left), (TR = trunk, P = pelvis, T = thigh, S = shank, and F = foot), (X = sagittal, Y = coronal, and Z = transverse planes).

2.3. Processing

Dynamic trials were digitised using Qualisys Track Manager (Qualisys Medical AB, Gothenburg, Sweden) in order to identify anatomical and tracking markers, and then exported as C3D files to Visual 3D (C-Motion, Germantown, MD, USA). All data were linearly normalized to 100% of the stance phase. GRF data and marker trajectories were smoothed with cutoff frequencies of 50 Hz and 12 Hz, respectively, using a low-pass Butterworth 4th-order zero-lag filter. Lower extremity kinematics were quantified using an XYZ Cardan sequence of rotations (where X is flexion–extension, Y is ab/adduction, and is Z is internal–external rotation). Tibial internal rotation kinematics were also calculated as described by Eslami et al. [37]. Finally, in order to quantify contralateral pelvic drop, the coronal plane angle of the pelvic segment was quantified with respect to the laboratory. The following three-dimensional kinematic measures were extracted for statistical analysis: (1) angle at footstrike; (2) peak angle; and (3) range of motion (representing the angular displacement from footstrike to peak angle). Running speed was also quantified within Visual 3D, using the linear velocity of the model centre of mass in the anterior direction.

In accordance with the protocol of Addison and Lieberman, [38], an impulse–momentum modelling approach was utilized to calculate effective mass as a percentage of bodyweight (% BW), which was quantified in accordance with the following equation:

$$\text{Effective mass} = \text{vertical GRF integral}/(\Delta \text{ foot vertical velocity} + \text{gravity} * \Delta \text{ time})$$

The impact peak was defined in the maximal and traditional running shoes as the first peak in vertical GRF. The time to impact peak (Δ time) was quantified as the duration from footstrike to impact peak. For runners who lacked an impact peak, in accordance with Sinclair et al. [39], we calculated the relative position of the impact peak as a percentage of the stance phase, based on a mean of the other runners, and positioned the impact peak here in those who did not exhibit a disenable peak in the vertical GRF–time curve. The vertical GRF integral during the period of the impact peak was calculated using a trapezoidal function. The change in foot vertical velocity (Δ foot vertical velocity) was determined as the change in vertical foot velocity between the instances of footstrike and the impact peak [40]. The velocity of the foot was quantified using the centre of mass of the foot segment in the vertical direction, within Visual 3D [39].

The loading rate, expressed as bodyweight per second (BW/s), was also extracted by obtaining the peak increase in vertical GRF between adjacent data points using the first derivative function within Visual 3D. Furthermore, the GRF impulse expressed as bodyweight per millisecond (BW·ms) during the stance phase in all three anatomical directions was calculated using a trapezoidal function. The strike index (%) was calculated as the position of the centre of pressure location at footstrike, relative to the total length of the foot [41] (Figure 2a–c). A strike index of 0–33.3% denotes a rearfoot, 33.4–66.6% a midfoot, and 66.7–100% a forefoot strike pattern. Finally, vertical limb stiffness during running was quantified using a mathematical spring–mass model [42]. Vertical limb stiffness expressed as bodyweight per metre (BW/m) was calculated from the ratio of the peak vertical GRF normalized to bodyweight (BW) to the maximum vertical compression of the leg spring, which was calculated as the change in limb length from footstrike to minimum length during the stance phase [43]. Limb length (m) was quantified as the vertical height of the proximal end of the thigh segment within Visual 3D.

Following this, data during the stance phase were exported from Visual 3D into OpenSim 3.3 software (Simtk.org). A validated musculoskeletal model was used to process the biomechanical data, which were scaled to account for the anthropometrics of each runner. The model with 12 segments, 19 degrees of freedom, and 92 musculotendon actuators [44] was used to estimate lower extremity muscle and joint forces. A residual reduction algorithm [22] was first used to resolve dynamic inconsistency between the kinematics of the measured GRF and the model, and muscle kinetics were then quantified using static optimization, as described by Steele et al. [45].

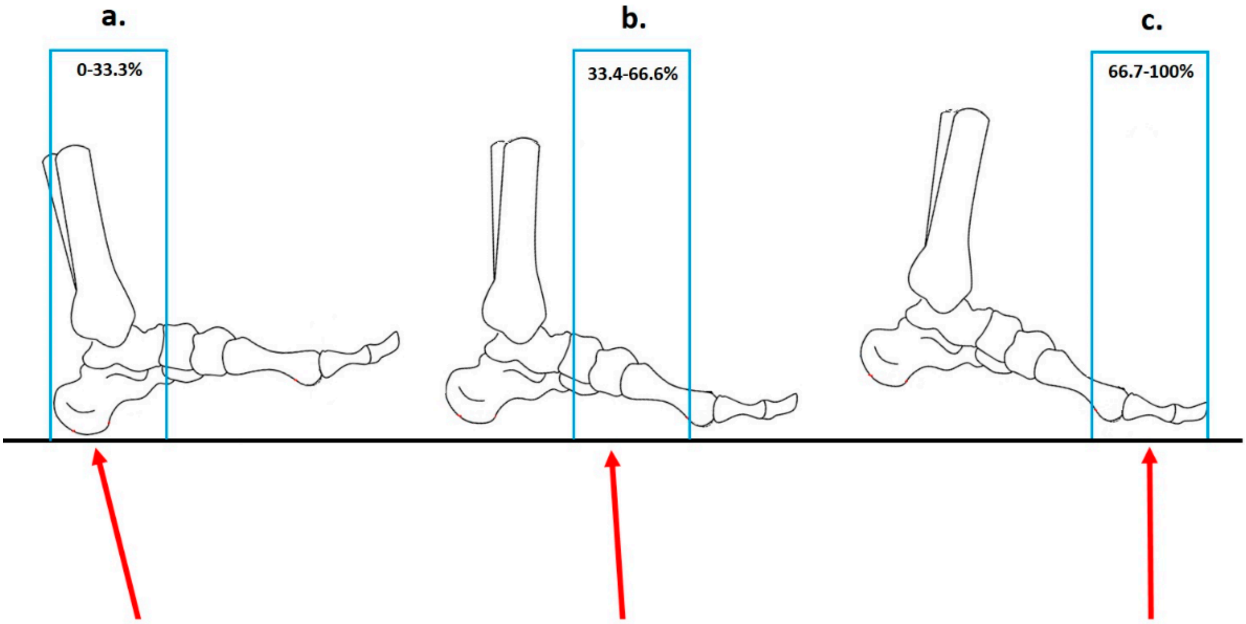

Figure 2. Definitions of footstrike modalities according to the strike index [39] (**a**) Rearfoot strike; (**b**) midfoot strike; and (**c**) forefoot strike.

From the above static optimization processes, the peak model muscle forces during the stance phase were extracted after being normalized to bodyweight (BW). Furthermore, the impulses (BW·ms) during the stance phases for the aforementioned muscles were also extracted using a trapezoidal function. In addition, the biceps femoris long-head, biceps femoris short-head, semitendinosus, and semimembranosus muscle forces were summed to create the total hamstring muscle force, while the rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius forces were also summed to create the total quadriceps muscle force. The peak total hamstring and quadriceps forces, as well as their impulses during the stance phase, were also extracted. In accordance with Besier et al. [23], the mean (%) contributions of each of the individual hamstring and quadriceps muscles to the total hamstring and total quadriceps forces during the stance phase were quantified. Finally, the mean co-contraction ratio was calculated by dividing the total hamstring force impulse by the total quadriceps impulse and peak co-contraction ratio, by dividing the total hamstring force at the instance of peak patellofemoral force by the total quadriceps force at the same time point.

As muscle forces are the main determinant of joint compressive forces [46], following the static optimization process the peak compressive patellofemoral joint force (BW) was calculated via the joint reaction analysis function, using the muscle forces generated from the static optimization process as inputs [22]. Furthermore, peak patellofemoral stress, expressed as kilopascals per bodyweight (KPa/BW), was quantified by dividing the patellofemoral force by the joint contact area. Patellofemoral contact areas were obtained by fitting a polynomial curve to the sex-specific data of Besier et al. [47], who estimated patellofemoral contact areas as a function of the knee flexion angle using magnetic resonance imaging. In addition, peak patellofemoral force (BW·ms) and stress (expressed as kilopascals per bodyweight per millisecond—KPa/BW·ms) impulses during the stance phase were extracted, also using a trapezoidal function. Finally, patellofemoral force/stress load rates (BW/s and KPa/BW/s, i.e., kilopascals per bodyweight per second) were extracted by obtaining the maximum increase in force/stress between adjacent data points using a first derivative function.

In addition to the above, the patellofemoral force (BW) and patellofemoral stress (KPa/BW) experienced per mile were also quantified in order to explore the effect of step length on loading at this joint [48]. The number of steps needed to complete 1 mile was quantified using the step length (m), which was determined by taking the difference in the horizontal position of the foot's centre of mass between the right and left limbs at footstrike from each running trial [49]. To obtain the force/stress experienced per mile, impulse values for these measures outlined above were multiplied by the number of steps required to run a mile.

2.4. Statistical Analyses

For each outcome variable and group, means and standard deviations (SD) were calculated. Differences between four pairs of group comparisons were undertaken: (1) Overall PFP vs. control groups were contrasted, which involved all PFP runners compared against all of the asymptomatic runners. Following this subset, analyses of (2) male PFP vs. male control, (3) female PFP vs. female control, and (4) male PFP vs. female PFP were undertaken. To compare participant characteristics (i.e., age, mass, stature, BMI, running speed, step length, mean weekly running volume), linear mixed models with group modelled as a fixed factor and random intercepts by participants were adopted in order to compare pairs 1–4; symptom duration and KOOS-PF were comparable in pair 4 only.

To compare biomechanical outcomes across the four pairs of groups, the same approach was adopted, adjusting only for running speed, which was modelled as a continuous fixed covariate. In addition, for group comparisons from pairs 1–3 outlined above, binary logistic regression analysis was conducted with the biomechanical parameters as the predictor variables and classification into either the PFP or the control group as the outcome variable. Finally, two-way Pearson's chi-squared (X^2) tests of independence with probability values calculated by Monte Carlo simulation were used to assess differences in the distribution of the three footstrike patterns between the pairs. Only parameters identified as being significantly different between control and PFP groups using linear mixed-model analyses were considered for the regression analyses. All statistical analyses were conducted using SPSS v27 (IBM, SPSS). For linear mixed models, the mean difference (b), t-value, and 95% confidence intervals of the difference are presented. For binary logistic regression analyses, the odds ratios (ORs) and 95% confidence intervals of the odds ratios are presented. Odds ratio's represented the odds of being classified into the PFP group for every 1 unit increase in the predictor variable. Statistical significance for all analyses was accepted at the $p < 0.05$ level. In the interests of conciseness and clarity, only variables that presented with statistical significance are presented in the Results section.

3. Results

3.1. Participant Characteristics

Comparisons between all groups for age, BMI, running speed, mean weekly running volume, symptom duration, and KOOS-PF were non-significant (p = 0.12–0.97). However, mass (b = 15.98 (95% CI = 7.25–24.69), t = 3.71, $p < 0.001$) and stature (b = 0.11 (95% CI = 0.08–0.15), t = 5.68, $p < 0.001$) were significantly greater in symptomatic males compared to females with PFP. Furthermore, step length was shown to be significantly greater in the control group compared to overall PFP (b = 0.27 (95% CI = 0.14–0.40), t = 4.023, $p < 0.001$) and in male controls compared to male PFP runners (b = 0.15 (95% CI = 0.07–0.22), t = 4.067, $p < 0.001$) (Table 1).

3.2. Overall PFP vs. Control

Knee flexion at footstrike, knee external rotation at footstrike, peak knee flexion, knee coronal plane ROM, knee transverse plane ROM, and ankle transverse plane ROM were significantly greater in the control group. Hip external rotation at footstrike, hip sagittal plane ROM, knee abduction at footstrike, ankle eversion at footstrike, ankle external rotation at footstrike, peak ankle eversion, and pelvic ROM were significantly greater in the PFP group (Table 2).

In addition, the strike index was significantly greater in the control group. The patellofemoral force per mile and patellofemoral stress per mile were significantly larger in the PFP group (Table 3).

The peak adductor longus force, flexor digitorum longus impulse, flexor hallucis longus impulse, gluteus minimus impulse, peroneus tertius impulse, semitendinosus impulse, peak semitendinosus force, soleus impulse, semitendinosus %, vastus intermedius %, vastus lateralis %, vastus medialis, and mean co-contraction ratio were significantly greater in the control group. The peak extensor hallucis longus force, peak lateral gastrocnemius force, rectus femoris impulse, peak semimembranosus force, biceps femoris short head %, and rectus femoris % were significantly greater in the PFP group (Table 4).

The control group comprised 25 rearfoot strikers, 11 midfoot strikers, and 4 forefoot strikers, whereas the PFP group had 37 rearfoot strikers, 2 midfoot strikers, and 1 forefoot striker. The chi-squared test was significant ($X^2{}_{(2)} = 10.35$, $p = 0.006$), with statistically more rearfoot strikers in the PFP group, and more mid- and forefoot strikers in the control group.

3.3. Male PFP vs. Male Control

The ankle transverse plane ROM was significantly greater in the control group. The ankle eversion at footstrike, ankle internal rotation at footstrike, peak ankle eversion, and pelvic ROM were significantly greater in the PFP group (Table 5).

In addition, adductor magnus impulse, gluteus minimus impulse, peroneus brevis impulse, peak peroneus brevis force, semitendinosus impulse, peak semitendinosus force, peak soleus force, semitendinosus %, vastus intermedius %, vastus lateralis %, and vastus medialis % were significantly greater in the control group; rectus femoris %, however, was significantly greater in the PFP group (Table 6).

The control group comprised 19 rearfoot strikers, 4 midfoot strikers, and 2 forefoot strikers, whereas the male PFP group had 22 rearfoot strikers, 2 midfoot strikers, and 1 forefoot striker. The chi-squared test was non-significant ($X^2{}_{(2)} = 1.56$, $p = 0.458$).

3.4. Female PFP vs. Female Control

Knee external rotation at footstrike and knee transverse plane ROM were significantly greater in the control group. Knee abduction at footstrike, ankle dorsiflexion at footstrike, ankle eversion at footstrike, ankle external rotation at footstrike, peak ankle dorsiflexion, peak ankle eversion, and pelvic ROM were significantly greater in the PFP group (Table 7).

In addition, the strike index was significantly greater in the control group. The vertical GRF impulse, patellofemoral force impulse, peak patellofemoral force, peak patellofemoral stress, patellofemoral stress loading rate, patellofemoral stress impulse, and patellofemoral stress per mile were significantly greater in the PFP group (Table 8).

Peak adductor longus force, semitendinosus %, vastus intermedius %, vastus lateralis %, and vastus medialis % were significantly greater in the control group. Peak biceps femoris short-head force, peak extensor hallucis longus force, peak lateral gastrocnemius force, peak medial gastrocnemius force, peak peroneus longus force, psoas impulse, rectus femoris impulse, peak semimembranosus force, total quadriceps impulse, peak total quadriceps force, peak vastus intermedius force, vastus intermedius impulse, peak vastus medialis force, vastus medialis impulse, and rectus femoris % were significantly greater in the PFP group (Table 9).

Table 1. Participant characteristics.

	Control		PFP		Male Control		Male PFP		Female Control		Female PFP	
	Mean	***SD***	**Mean**	***SD***	**Mean**	***SD***	**Mean**	***SD***	**Mean**	***SD***	**Mean**	***SD***
Age (years)	33.25	10.78	35.85	9.29	33.87	10.42	36.60	9.07	32.76	11.55	34.60	9.83
Mass (kg)	70.91	9.65	73.01	15.19	75.65	9.81	80.00	14.59	65.21	8.31	64.02	10.34
Stature (m)	1.73	0.09	1.73	0.08	1.74	0.07	1.77	0.07	1.68	0.10	1.66	0.04
BMI (kg/m^2)	24.55	3.26	24.46	3.36	23.79	3.00	25.39	3.44	23.22	3.66	23.20	2.83
Speed (m/s)	3.89	0.43	3.66	0.58	3.90	0.52	3.72	0.60	3.86	0.27	3.56	0.55
Step length (m)	1.47	0.36	1.20	0.23	1.50	0.29	1.21	0.23	1.43	0.45	1.19	0.24
Mean weekly running volume (km)	27.12	15.51	30.09	19.62	29.04	19.14	30.94	19.72	25.21	10.96	29.24	19.99
Symptom duration (months)	*N/A*		48.73	32.06	*N/A*		42.32	26.84	*N/A*		55.13	36.10
KOOS-PF	*N/A*		61.25	15.37	*N/A*		58.10	15.34	*N/A*		66.50	14.40

Table 2. Three-dimensional kinematics in overall PFP participants and controls.

		Control		Patellofemoral							
		Mean	***SD***	**Mean**	***SD***	***t***	***b***	***b (95% CI)***	***p***	***OR***	***OR (95% CI)***
Sagittal plane	Hip ROM (°)	0.60	1.12	1.78	1.93	3.39	1.21	0.50–1.92	0.001	1.75	1.18–2.59
	Knee angle at footstrike (°)	16.83	8.81	11.85	5.41	3.17	5.23	1.95–8.51	0.002	0.90	0.83–0.97
	Peak knee flexion (°)	43.95	6.71	40.29	7.80	2.08	3.41	0.15–6.68	0.041	0.93	0.873–1.00
Coronal plane	Pelvic ROM (°)	1.73	1.45	3.16	2.05	3.33	1.32	0.53–2.12	0.001	1.54	1.15–2.05
	Knee angle at footstrike (°)	0.50	5.23	−2.71	4.63	2.69	2.99	0.78–5.20	0.009	0.88	0.80–0.97
	Knee ROM (°)	6.31	4.06	3.83	2.58	3.14	2.41	0.88–3.94	0.002	0.81	0.70–0.94
	Ankle angle at footstrike (°)	5.66	5.04	−4.39	6.05	8.02	10.10	7.59–12.60	<0.001	0.70	0.60–0.82
	Peak ankle eversion (°)	−8.15	4.19	−15.09	7.39	5.26	7.12	4.43–9.82	<0.001	0.78	0.70–0.88
Transverse plane	Hip angle at footstrike (°)	3.66	10.30	−1.45	9.50	2.08	4.64	0.20–9.07	0.041	0.95	0.91–1.01
	Knee angle at footstrike (°)	−9.96	8.62	−4.61	7.75	2.66	4.90	1.23–8.56	0.009	1.08	1.01–1.15
	Knee ROM (°)	17.48	6.66	12.98	4.86	3.08	3.98	1.42–6.56	0.003	0.88	0.80–0.97
	Ankle angle at footstrike (°)	−6.38	7.90	−15.68	4.74	6.37	9.38	6.45–12.32	<0.001	0.80	0.721–0.89
	Ankle ROM (°)	7.82	4.16	0.61	1.03	10.42	7.11	5.75–8.47	<0.001	0.35	0.21–0.56

Table 3. Joint loading and temporal indices in overall PFP participants and controls.

	Control		Patellofemoral							
	Mean	***SD***	**Mean**	***SD***	***t***	***b***	***b* (95% CI)**	***p***	***OR***	***OR* (95% CI)**
Strike index (%)	33.57	22.09	17.75	16.43	3.52	15.47	6.71–24.22	0.001	0.946	0.91–0.98
Step length (m)	1.47	0.36	1.20	0.23	3.65	0.24	0.11–0.38	<0.001	0.043	0.01–0.33
Patellofemoral force per mile (BW)	440.24	204.84	550.33	192.08	2.14	94.46	6.55–182.37	0.036	1.003	1.00–1.01
Patellofemoral stress per mile (KPa/BW)	812.93	363.66	1047.49	333.02	2.64	203.77	50.07–357.47	0.01	1.002	1.001–1.004

Table 4. Muscle force indices in overall PFP participants and controls.

	Control		Patellofemoral							
	Mean	***SD***	**Mean**	***SD***	***t***	***b***	***b* (95% CI)**	***p***	***OR***	***OR* (95% CI)**
Peak adductor longus force (BW)	0.74	0.38	0.54	0.27	2.57	0.19	0.04–0.34	0.012	0.17	0.04–0.74
Peak extensor hallucis longus force (BW)	0.22	0.09	0.28	0.09	2.77	0.06	0.02–0.10	0.007	724.81	7.72–111,369.08
Flexor digitorum longus impulse (BW·ms)	10.03	5.46	7.03	2.88	2.77	2.70	0.76–4.64	0.007	0.83	0.71–0.968
Flexor hallucis longus impulse (BW·ms)	10.76	6.95	7.57	3.55	2.56	3.20	0.72–5.69	0.012	0.86	0.76–0.99
Gluteus minimus impulse (BW·ms)	130.34	35.28	115.47	24.33	2.75	18.22	5.02–31.42	0.007	0.98	0.96–1.00
Peak lateral gastrocnemius force (BW)	0.86	0.24	0.96	0.19	2.13	0.10	0.01–0.20	0.036	11.22	1.10–114.35
Peroneus tertius impulse (BW·ms)	8.22	3.30	5.84	2.62	3.07	1.96	0.69–3.24	0.003	0.77	0.64–0.94
Rectus femoris impulse (BW·ms)	166.05	76.86	225.19	52.79	3.87	57.54	27.91–87.16	<0.001	1.01	1.01–1.02
Peak semimembranosus force (BW)	0.52	0.13	0.65	0.20	3.06	0.11	0.04–0.18	0.003	90.44	3.75–2184.09
Semitendinosus impulse (BW·ms)	21.01	7.18	12.30	8.53	4.81	8.56	5.02–12.11	<0.001	0.88	0.82–0.94
Peak semitendinosus force (BW)	0.31	0.07	0.24	0.12	3.00	0.07	0.02–0.11	0.004	0.01	0.00–0.14
Soleus impulse (BW·ms)	467.68	118.87	396.30	80.47	3.33	76.05	30.62–121.48	0.001	0.99	0.99–1.00
Biceps femoris short-head (%)	30.62	8.92	34.42	11.11	2.10	4.69	0.24–9.13	0.039	1.055	1.00–1.11
Semitendinosus (%)	15.68	4.60	9.51	4.62	5.70	5.89	3.83–7.94	<0.001	0.768	0.68–0.87
Rectus femoris (%)	19.49	4.97	25.97	7.25	4.64	6.52	3.72–9.31	<0.001	1.260	1.11–1.43
Vastus intermedius (%)	23.38	1.36	21.50	2.02	4.84	1.88	1.11–2.66	<0.001	0.405	0.25–0.65
Vastus lateralis (%)	35.95	2.78	33.20	3.53	3.88	2.79	1.36–4.21	<0.001	0.721	0.59–0.88
Vastus medialis (%)	21.17	1.35	19.33	1.83	5.07	1.85	1.12–2.57	<0.001	0.36	0.22–0.61
Mean co-contraction ratio	0.19	0.09	0.15	0.07	2.06	0.04	0.001–0.07	0.043	0.002	0.00–0.86

Table 5. Three-dimensional kinematics in male PFP participants and controls.

		Male Control		Male PFP							
		Mean	SD	Mean	SD	t	b	b (95% CI)	p	OR	OR (95% CI)
Coronal plane	Pelvic ROM (°)	1.62	1.40	2.88	1.99	2.34	0.57	0.08–1.06	0.023	1.51	1.03–2.20
	Ankle angle at footstrike (°)	5.35	4.72	−4.06	5.21	6.85	4.83	3.41–6.25	$p < 0.001$	0.67	0.54–0.83
	Peak ankle eversion (°)	−8.05	3.48	−14.69	6.13	5.07	3.53	2.13–4.93	$p < 0.001$	0.68	0.54–0.86
Transverse plane	Ankle angle at footstrike (°)	−8.77	8.15	−15.33	5.49	3.40	3.35	1.37–5.33	0.001	0.86	0.78–0.96
	Ankle ROM (°)	7.24	3.91	0.69	1.12	8.02	3.24	2.43–4.04	$p < 0.001$	0.37	0.22–0.64

Table 6. Muscle force indices in male PFP participants and controls.

	Male Control		Male PFP							
	Mean	SD	Mean	SD	t	b	b (95% CI)	p	OR	OR (95% CI)
Adductor magnus impulse (BW·ms)	53.33	30.55	36.75	19.79	2.61	9.27	2.13–16.41	0.012	*0.97*	*0.94–1.00*
Gluteus minimus impulse (BW·ms)	126.55	38.37	108.45	24.42	2.32	10.28	1.37–19.19	0.025	0.98	0.96–1.01
Peroneus brevis impulse (BW·ms)	51.55	24.23	37.05	23.70	2.33	7.88	1.07–14.69	0.024	0.97	0.95–0.99
Peak peroneus brevis force (BW)	0.60	0.21	0.46	0.22	2.27	0.07	0.01–0.13	0.028	0.04	0.004–0.85
Semitendinosus impulse (BW·ms)	20.27	7.44	9.98	7.95	4.66	5.15	0.293–7.38	<0.001	0.85	0.77–0.93
Peak semitendinosus force (BW)	0.30	0.08	0.20	0.11	3.67	0.05	0.02–0.08	0.001	0.003	0.001–0.03
Soleus impulse (BW·ms)	464.90	135.71	383.28	73.12	2.74	42.16	11.22–73.10	0.009	0.99	0.98–1.00
Semitendinosus (%)	15.53	4.18	8.87	4.77	5.06	3.24	1.95–4.52	<0.001	0.74	0.63–0.88
Rectus femoris (%)	21.30	3.80	28.08	7.69	3.75	3.28	1.52–5.04	<0.001	1.321	1.10–1.59
Vastus intermedius (%)	23.04	1.13	20.98	2.18	4.01	1.01	0.50–1.51	<0.001	0.330	0.16–0.67
Vastus lateralis (%)	34.72	2.08	32.02	3.58	3.07	1.29	0.45–2.14	0.004	0.678	0.51–0.91
Vastus medialis (%)	20.94	1.07	18.92	2.04	4.18	0.99	0.51–1.46	<0.001	0.283	0.13–0.63

Table 7. Three-dimensional kinematics in female PFP participants and controls.

		Female Control		Female PFP							
		Mean	SD	Mean	SD	t	b	b (95% CI)	p	OR	OR (95% CI)
Sagittal plane	Ankle angle at footstrike (°)	3.36	10.78	10.36	4.67	2.05	3.15	0.02–6.29	0.049	1.18	1.00–1.38
	Peak dorsiflexion (°)	16.51	4.29	20.19	3.12	2.73	1.88	0.05–3.29	0.01	1.35	1.04–1.74
Coronal plane	Pelvic ROM (°)	1.88	1.54	3.64	2.13	2.68	0.90	0.21–1.59	0.011	1.64	1.04–2.58
	Knee angle at footstrike (°)	1.16	5.38	−4.62	3.82	3.30	2.84	1.09–4.59	0.002	0.76	0.61–0.94
	Ankle angle at footstrike (°)	6.09	5.55	−4.93	7.41	4.39	5.10	2.73–7.47	$p < 0.001$	0.75	0.60–0.93
	Peak ankle eversion (°)	−8.28	5.11	−15.75	9.32	2.49	3.30	0.60–6.00	0.018	0.86	0.75–0.99
Transverse plane	Knee angle at footstrike (°)	−12.32	7.83	−1.95	7.06	3.64	4.95	2.18–7.72	0.001	1.22	1.04–1.42
	Knee ROM (°)	17.88	5.82	10.39	3.88	3.76	3.34	1.58–5.15	0.001	0.75	0.60–0.94

Table 8. Joint loading and temporal indices in female PFP participants and controls.

	Female Control		Female PFP							
	Mean	***SD***	**Mean**	***SD***	***t***	***b***	***b* (95% CI)**	***p***	***OR***	***OR* (95% CI)**
Patellofemoral impulse (BW·ms)	655.07	192.48	817.74	125.04	2.51	74.88	14.18–135.59	0.017	1.01	1.00–1.02
Peak patellofemoral force (BW)	6.13	1.79	7.31	1.08	2.13	0.58	0.02–1.14	0.041	1.73	1.01–2.98
Peak patellofemoral stress (KPa/BW)	10.82	2.86	13.07	1.71	2.54	1.11	0.22–2.00	0.016	1.53	1.06–2.21
Patellofemoral stress loading rate (KPa/BW/s)	318.53	124.27	402.55	129.66	2.52	55.48	10.60–100.36	0.017	1.01	1.00–1.02
Patellofemoral stress impulse (KPa/BW·ms)	1205.92	314.27	1567.44	192.80	3.50	167.22	70.00–264.45	0.001	1.00	1.00–1.02
Patellofemoral stress per mile (BW)	764.95	429.71	1116.67	361.68	2.64	203.77	50.07–357.46	0.01	1.01	1.00–1.02
Vertical GRF impulse (BW·ms)	309.02	34.06	354.18	37.04	3.17	20.13	7.21–33.06	0.003	1.04	1.01–1.07
Strike index (%)	40.20	21.69	15.49	3.37	3.94	11.29	5.45–17.13	$p < 0.001$	0.79	0.65–0.95

Table 9. Muscle force indices in female PFP participants and controls.

	Female Control		Female PFP							
	Mean	***SD***	**Mean**	***SD***	***t***	***b***	***b* (95% CI)**	***p***	***OR***	***OR* (95% CI)**
Peak adductor longus force (BW)	0.75	0.41	0.51	0.24	2.07	0.13	*0.06–0.16*	0.043	0.21	*0.01–0.97*
Peak biceps femoris force (BW)	0.80	0.23	1.01	0.28	2.52	0.12	0.02–0.21	0.017	55.52	1.47–2091.52
Peak extensor hallucis longus force (BW)	0.17	0.06	0.27	0.12	2.89	0.05	0.01–0.09	0.007	215,238	4.57–10,134,951,829.16
Peak lateral gastrocnemius force (BW)	0.81	0.24	1.02	0.18	2.59	0.10	0.02–0.18	0.014	199.27	2.16–18,373.01
Peak medial gastrocnemius force (BW)	1.79	0.24	2.12	0.33	3.38	0.17	0.07–0.28	0.002	305.1	2.72–34,221.81
Peak peroneus longus force (BW)	0.95	0.25	1.29	0.37	3.34	0.19	0.07–0.30	0.002	49.52	2.37–1035.09
Psoas major impulse (BW·ms)	83.49	35.93	125.46	45.12	3.07	22.54	7.60–37.48	0.004	1.03	1.00–1.06
Rectus femoris impulse (BW·ms)	117.08	49.13	199.54	49.23	4.69	41.97	23.72–60.21	$p < 0.001$	1.04	1.01–1.07
Peak semimembranosus force (BW)	0.52	0.15	0.75	0.19	3.36	0.09	0.04–0.15	0.002	2323.7	5.15–1,047,595.46
Total quadriceps force impulse (BW·ms)	675.62	171.35	891.41	117.88	3.78	101.72	46.84–156.60	0.001	1.01	1.00–1.02
Peak total quadriceps force (BW)	5.88	1.52	7.18	1.05	2.68	0.64	0.15–1.14	0.012	2.05	1.07–3.92
Vastus intermedius impulse (BW·ms)	160.63	40.36	199.77	29.64	2.75	17.73	4.59–30.86	0.01	1.03	1.00–1.05
Peak vastus intermedius impulse (BW·ms)	1.64	0.48	2.02	0.32	2.52	0.19	0.04–0.34	0.017	9.05	1.16–70.48
Vastus medialis impulse (BW·ms)	145.29	38.61	178.72	27.68	2.48	15.24	2.73–27.75	0.019	1.03	1.00–1.06
Peak vastus medialis force (BW)	1.50	0.45	1.83	0.31	2.32	0.17	0.02–0.31	0.027	8.48	1.02–70.87
Semitendinosus (%)	15.88	5.23	10.59	4.30	2.67	2.29	0.54–4.05	0.012	0.80	0.63–0.98
Rectus femoris (%)	17.06	5.42	22.46	4.88	3.21	2.99	1.09–4.89	0.003	1.27	1.05–1.54
Vastus intermedius (%)	23.84	1.53	22.38	1.39	2.99	0.79	0.25–1.33	0.005	0.45	0.23–0.88
Vastus lateralis (%)	37.62	2.79	35.17	2.46	3.00	1.41	0.45–2.38	0.005	0.66	0.47–0.93
Vastus medialis (%)	21.49	1.64	20.00	1.20	2.97	0.79	0.25–1.32	0.006	0.45	0.23–9.90

The control group comprised 7 rearfoot strikers, 6 midfoot strikers, and 2 forefoot strikers, whereas the female PFP group had 15 rearfoot strikers. The chi-squared test was significant ($X^2_{(2)} = 11.05$, $p = 0.004$), with statistically more rearfoot strikers in the female PFP group, and more mid- and forefoot strikers in the control group.

3.5. Male PFP vs. Female PFP

Hip flexion at footstrike, peak hip adduction, knee flexion at footstrike and peak knee flexion were significantly greater in the female PFP group; knee transverse plane ROM was significantly greater in the male PFP group (Table 10).

Table 10. Three-dimensional kinematics in male and female PFP participants.

		Male PFP		Female PFP					
		Mean	***SD***	**Mean**	***SD***	***t***	***b***	***b* (95% CI)**	***p***
Sagittal plane	Hip angle at footstrike (°)	31.30	8.46	39.54	7.02	3.55	8.79	3.79–13.79	0.001
	Knee angle at footstrike (°)	10.15	4.69	14.69	5.49	2.89	4.62	1.38–7.86	0.006
	Peak knee flexion (°)	38.32	8.51	43.59	5.17	2.54	5.83	1.19–10.48	0.015
Coronal plane	Peak hip adduction (°)	7.62	5.73	11.30	2.71	2.38	3.71	0.57–6.85	0.02
Transverse plane	Knee ROM (°)	14.53	4.80	10.39	3.88	2.75	3.80	1.00–6.59	0.009

The loading rate was significantly greater in the female PFP group (Table 11).

Table 11. Joint loading and temporal indices in male and female PFP participants.

	Male PFP		Female PFP					
	Mean	***SD***	**Mean**	***SD***	***t***	***b***	***b* (95% CI)**	***p***
Loading rate (BW/s)	150.08	45.89	173.28	39.12	2.18	27.91	1.97–53.85	0.036

Biceps femoris long-head impulse, peak biceps femoris short-head force, gluteus maximus impulse, peak gluteus maximus force, gluteus medius impulse, peak gluteus medius force, gluteus minimus impulse, peak gluteus minimus force, peak gracilis force, peak iliacus force, peak sartorius force, semimembranosus impulse, peak semimembranosus force, semitendinosus impulse, peak semitendinosus force, tensor fasciae latae impulse, peak tensor fasciae latae force, tibialis anterior impulse, total hamstring impulse, peak total hamstring force, vastus intermedius %, vastus lateralis %, mean co-contraction ratio, and peak co-contraction ratio were significantly greater in the female PFP group; extensor digitorum longus impulse, flexor digitorum longus impulse, rectus femoris impulse and rectus femoris % were significantly greater in the male PFP group (Table 12).

The male PFP group was comprised of 2 rearfoot strikers, 1 midfoot striker, and 1 forefoot striker, whereas the female PFP group had 15 rearfoot strike runners. The chi-squared test was non-significant ($X^2_{(2)} = 1.95$, $p = 0.378$).

Table 12. Muscle force indices in male and female PFP participants.

	Male PFP		Female PFP					
	Mean	***SD***	**Mean**	***SD***	***t***	***b***	***b* (95% CI)**	***p***
Biceps femoris long-head (BW·ms)	21.13	11.36	31.88	16.29	2.55	10.96	2.28–19.64	0.015
Peak biceps femoris short-head force (BW)	0.81	0.31	1.01	0.28	2.45	0.22	0.04–0.41	0.019
Flexor digitorum longus impulse (BW·ms)	47.30	24.94	28.09	12.48	2.69	17.73	4.41–31.04	0.01
Flexor hallucis longus impulse (BW·ms)	6.40	2.78	8.06	2.82	2.29	1.93	0.23–3.63	0.027
Peak gluteus maximus force (BW)	142.04	48.48	178.45	45.06	2.47	37.41	6.82–67.99	0.018
Gluteus maximus impulse (BW·ms)	1.40	0.45	1.69	0.42	2.81	0.35	0.10–0.60	0.008
Gluteus medius impulse (BW·ms)	261.79	58.62	320.89	48.67	3.24	54.01	20.31–87.72	0.002
Peak gluteus medius force (BW)	2.25	0.45	2.66	0.46	2.76	0.39	0.11–0.68	0.009
Gluteus minimus impulse (BW·ms)	108.45	24.42	127.16	19.81	2.43	17.46	2.94–31.98	0.02
Peak gluteus minimus force (BW)	0.95	0.21	1.16	0.22	3.00	0.20	0.07–0.34	0.005
Peak gracilis force (BW)	0.08	0.05	0.11	0.04	2.93	0.04	0.01–0.06	0.006
Peak iliacus force (BW)	2.01	0.39	2.40	0.37	3.48	0.42	0.17–0.66	0.0012
Rectus femoris impulse (BW·ms)	240.58	49.58	199.54	49.23	2.55	40.50	8.42–72.58	0.015
Peak sartorius force (BW)	0.24	0.05	0.30	0.05	3.76	0.06	0.03–0.09	0.001
Peak semimembranosus impulse (BW·ms)	36.65	15.54	55.55	19.95	3.30	17.59	6.80–28.38	0.002
Peak semimembranosus force (BW)	0.58	0.17	0.75	0.19	2.91	0.16	0.05–0.27	0.0059
Semitendinosus impulse (BW·ms)	9.98	7.95	16.17	8.28	2.54	6.51	1.32–11.70	0.015
Peak semitendinosus force (BW)	0.20	0.11	0.30	0.13	2.96	0.11	0.03–0.18	0.005
Tensor fasciae latae impulse (BW·ms)	55.82	10.98	66.03	9.17	3.04	10.08	3.37–16.80	0.004
Peak tensor fasciae latae force (BW)	0.45	0.08	0.57	0.07	4.98	0.12	0.07–0.16	$p < 0.001$
Tibialis impulse (BW·ms)	25.39	14.36	34.54	11.76	2.94	10.99	3.44–18.55	0.005

Table 12. *Cont.*

	Male PFP		Female PFP					
	Mean	***SD***	**Mean**	***SD***	***t***	***b***	***b* (95% CI)**	***p***
Total hamstring impulse (BW·ms)	108.48	36.77	147.66	45.69	3.02	39.05	12.90–65.21	0.004
Peak total hamstring force (BW)	1.39	0.47	1.66	0.46	2.01	0.29	0.06–0.59	0.048
Rectus femoris (%)	28.08	7.69	22.46	4.88	2.67	5.79	1.40–10.18	0.011
Vastus intermedius (%)	20.98	2.18	22.38	1.39	2.38	1.46	0.22–2.70	0.022
Vastus lateralis (%)	32.02	3.58	35.17	2.46	3.10	3.20	1.11–5.28	0.004
Mean co-contraction ratio	0.13	0.07	0.19	0.06	2.34	0.05	0.006–0.09	0.024
Peak co-contraction ratio	0.19	0.08	0.25	0.09	2.12	0.06	0.003–0.12	0.04

4. Discussion

Using a retrospective case–control approach, this study evaluated running biomechanics in patients with and without PFP via a musculoskeletal simulation-based approach, and also investigated potential distinctions in PFP presentation between the sexes. This study represents the first exploration of the biomechanical parameters linked to the aetiology of PFP using musculoskeletal simulation, and may yield important clinical information for efforts towards the cessation of symptom initiation and the improvement of PFP management.

Notably, patellofemoral stress indices were statistically greater in the PFP group compared to controls. This supports the notion that, in runners, PFP is mediated by increased joint loading, and is consistent with the findings of Brechter and Powers [50], who found enhanced patellofemoral joint stress in those with PFP, using a mixed sample. The subset analyses from this study importantly revealed that enhanced patellofemoral joint stress in PFP runners was driven by female sex, as no differences were evident in males. The female PFP group exhibited more pronounced and coherent differences in patellofemoral joint loading, importantly highlighting potential sex differences in PFP aetiology. This emphasizes the need for different treatment approaches in male and female runners, and management strategies seeking to reduce patellofemoral joint stress are likely to be most efficacious in female runners. Patellofemoral joint loading is primarily caused by forces generated within the quadriceps [51]; therefore, enhanced patellofemoral joint stress in the female PFP group was mediated as a function of the corresponding increases in forces that were observed consistently across all four quadriceps muscles.

A significantly more anterior footstrike position was shown in the control group in relation to the PFP group, which when contextualized via the strike index, revealed a rearfoot strike in the PFP group and a midfoot pattern in controls. The subset analyses again showed that this was mediated by female runners, and the chi-squared analyses support this, as significantly more rearfoot strikers were shown in the overall and female PFP groups. Daoud et al. [52] showed that runners who habitually adopt a rearfoot strike pattern are more than twice as likely to experience a chronic running injury. Crucially, this investigation lends further precision to this observation, as in female runners the utilization of a rearfoot strike pattern makes runners significantly more likely to experience PFP. It is likely that the increased quadriceps muscle forces and patellofemoral loading shown overall and in the female PFP group were mediated by the rearfoot strike pattern adopted in relation to control runners. Utilization of a rearfoot strike pattern places increased demands on the knee extensors [53], and patellofemoral stress is greater in rearfoot strikers [54]. From a clinical perspective, transitioning from a rearfoot strike pattern has been shown to attenuate patellofemoral joint loading and improve pain symptoms in male runners, although no such intervention has been undertaken in females [25]. Therefore, gait-retraining approaches that allow female PFP runners to modify their habitual footstrike pattern may be a particularly important clinical intervention.

From a kinematic and temporal perspective, peak knee flexion and step length were lower in the PFP group, while knee flexion was lower in male symptomatic runners compared to females with PFP. Individuals with PFP experience reduced knee flexion [55,56], which along with the reductions in step length may represent an attempt to minimise pain symptoms by mediating patellofemoral stress [49,55]. Reduced knee flexion in both the overall PFP and male PFP runners may be indicative of kinesiophobia—a renowned complaint in patients with PFP [10,56]. Kinesiophobia is more severe in males with chronic musculoskeletal pain [57,58]; therefore, as knee bracing [59] and exercise therapy [60] have been shown to improve kinesiophobia in PFP, this suggests that there is scope for targeted interventions towards male symptomatic runners.

The overall and male and female subset comparisons showed that peak eversion was significantly greater in PFP runners. Rearfoot eversion has been linked to the aetiology of PFP by theoretical modelling analyses [61], and Dierks et al. [18] showed significantly greater eversion in PFP runners in a mixed sample—though this investigation is the first to show increased eversion in sex-specific subset analyses. From a clinical standpoint, it appears that strategies centred around reducing rearfoot eversion are important for the treatment of PFP in both male and female runners. Conservative modalities such as foot orthoses and ankle braces have been shown to mediate statistical reductions in peak ankle eversion in both male and female runners [62,63]. No analyses have been undertaken using ankle bracing; however, previous intervention studies have shown foot orthoses to be effective in treating PFP, with greater rearfoot eversion angles at baseline predicting orthotic efficacy [64,65].

This investigation also revealed, in the comparisons of the overall and male and female subsets, that contralateral pelvic drop ROM was significantly greater in PFP runners. This is consistent with the findings of Bramah et al. [66]—who showed that injured runners demonstrated greater contralateral pelvic drop—and those of Willson and Davis [19], who indicated that runners with PFP exhibited significantly greater contralateral pelvic drop. Enhanced contralateral pelvic drop negatively influences patellofemoral joint biomechanics by elongating the ipsilateral iliotibial band, generating a greater laterally directed force on the patella [67,68]. Increased contralateral pelvic drop during weight-bearing activities and in PFP patients is considered a clinical sign of diminished strength or neuromuscular function at the hip [66], which results in diminished capacity to stabilize the pelvis. This investigation supports this notion, as forces in the muscles primarily involved in stabilizing the pelvis were found to be statistically greater in the control group across all of the aforementioned group comparisons. Importantly, real-time gait retraining has been shown to significantly attenuate contralateral pelvic drop and pain symptoms in runners with PFP, and hip strengthening is able to mediate statistical improvements in PFP pain symptoms [69]. The findings from the current investigation importantly support the collective utilization of these intervention modalities in runners of both sexes.

The overall as well as the male and female comparisons showed that % contributions of the rectus femoris were consistently greater in PFP runners, and that the same was true in symptomatic male runners. This suggests that overutilization of the rectus femoris is a potentially important biomechanical mechanism in PFP, and can be used to differentiate between sexes in symptomatic runners. Although, the mechanistic influence of this finding relating to the aetiology of PFP is not known, it is nevertheless a potentially clinically meaningful neuromuscular observation that may aid in the management of PFP in runners of both sexes. Furthermore, the overall and subgroup comparisons of symptomatic runners showed an enhanced co-contraction ratio in control runners and symptomatic females. This observation contrasts with those of Besier et al. [23], who found no differences between PFP runners and healthy controls during running, although this investigation utilized electromyography rather than muscle forces. Nevertheless, it is proposed that these observations are mediated as a function of the enhanced hamstring and reduced rectus femoris muscle forces that were evident in the above overall and subgroup comparisons. It remains unknown whether these alterations in muscle kinetics are adaptive in response to pain or if they are causative, but it can be speculated that increased co-contraction might enhance knee joint stability and benefit the position of the patella within the trochlear groove [70].

In contrast to the observations of both Willy et al. [20] and Neal et al. [4], our findings showed that females with PFP did not exhibit a greater peak hip adduction angle compared to controls. However, in agreement with Willy et al. [20], our results showed that female runners with PFP ran with statistically larger hip adduction in relation to symptomatic males. Previous intervention trials have shown that targeted gait retraining reduces peak hip adduction during running and improves pain and function in runners with PFP [71]. The observations from this investigation suggest that these interventions are likely to be most effective in females, and the implementation of gait retraining to attenuate hip adduction in symptomatic female runners is encouraged. Taking into account the range of sex-specific differences in the biomechanics of running between symptomatic runners demonstrates sex-specificity in terms of PFP presentation, indicating that future clinical investigations should present aetiological data for both sexes, and that treatment modalities should also be correspondingly sex-specific.

As with any investigation, there are limitations to the current study, and the findings should be contextualized in line with these limitations. Firstly, the retrospective nature of the study design means that it is not possible to determine whether the biomechanical differences between symptomatic runners and healthy controls are adaptations in the presence of anterior knee pain, or if they are causative parameters. Owing to the expense and difficulty of undertaking analyses of this nature, there is a lack of prospective analyses identifying risk factors for PFP, so this is a clear avenue for future research. In addition, PFP is a multifactorial condition; therefore, although the current investigation explored a plethora of parameters using musculoskeletal simulation, it was beyond the scope of this study to determine the non-biomechanical risk factors that may be important to the aetiology of PFP. Future analyses should seek to investigate additional measurements that may be important to the aetiology and clinical management of PFP.

5. Conclusions

This investigation augments the existing literature in clinical biomechanics by providing a retrospective exploration of the biomechanics of running in runners with and without PFP, using musculoskeletal simulation. With overall PFP as well as female PFP runners exhibiting enhanced patellofemoral stress in addition to a significantly lower strike index, peak eversion, and contralateral pelvic drop being greater in overall, male, and female PFP runners, symptomatic females exhibiting a significantly larger peak hip adduction compared to PFP males, and peak knee flexion being reduced in overall PFP and male PFP runners compared to symptomatic females, this investigation highlights potential risk factors for PFP that may be addressed through focused intervention modalities. Specifically, gait-retraining approaches allowing female PFP runners to modify their habitual footstrike pattern and attenuate hip joint adduction, foot orthoses to reduce eversion, targeted gait retraining to reduce pelvic drop in male and female PFP runners, and knee bracing and exercise therapy to mediate potential symptoms of kinesiophobia in male PFP runners, appear to represent particularly important clinical interventions.

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