THE INFLUENCE OF SPEED ON PATELLOFEMORAL JOINT KINETICS IN RECREATIONAL RUNNERS

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This study aimed to determine the influence of running speed on patellofemoral joint (PFJ) kinetics. Twenty recreational runners ran on an instrumented treadmill at four running speeds with simultaneous 3D motion capture. A musculoskeletal model derived peak and cumulative (per 1km of continuous running) PFJ force and stress for each speed. Peak PFJ force and stress significantly increased with faster speeds. In contrast, cumulative PFJ measures decreased with faster speeds. Running at faster speeds increases the magnitude of peak PFJ kinetics but conversely results in less accumulated force over a set distance. Clinicians and coaches should be aware of the relatively high PFJ cumulative force and stress associated with slow running (~2.5 m/s) and consider moderate-speed interval running as part of overuse knee injury prevention and management plans.

KEYWORDS: running, speed, biomechanics, patellofemoral joint, knee.

INTRODUCTION: Despite the numerous health benefits of running, the risk of sustaining a running-related injury is high (van Gent et al., 2007). The most commonly reported running-related injury is patellofemoral pain (PFP) (Francis et al., 2019; van Gent et al., 2007), which accounts for up to 17% of all running-related injuries (Francis et al., 2019).

PFP is characterised by an insidious onset of pain localised to the anterior retropatellar or peripatellar region of the knee (Willy et al., 2019). The aetiology of PFP is not fully understood and is considered to be multifactorial (Willy et al., 2019). Excessive patellofemoral joint (PFJ) loading is thought to contribute to the development and persistence of PFP (Powers et al., 2012; Willy et al., 2019). During running, the PFJ is exposed to forces of approximately 4-6 times body weight (Starbuck et al., 2021; Willy et al., 2016). This can result in upwards of 320 body weights accumulated per minute of running (Esculier et al., 2020).

PFP management strategies have often focused on reducing the relative force and stress (product of PFJ force per unit of contact area) on the PFJ (Willy et al., 2019). Load management advice has recommended reducing running *distance* and *speed* (Esculier et al., 2020). However, the influence of speed on PFJ kinetic remains unclear. PFP may be associated with higher training volumes rather than faster speeds (Starbuck et al., 2021). In high-level runners, slower running speeds were associated with lower PFJ forces than faster speeds, with no difference in cumulative PFJ force (Starbuck et al., 2021). However, these results may not be generalisable to recreational runners who experience comparatively higher rates of running-related injuries and may benefit the most from preventative interventions (Buist et al., 2010). Indeed, another study that included recreational runners observed greater cumulative knee extensor moment impulse during slower running speeds compared to faster speeds, primarily due to the increased number of steps required to complete the same distance (Petersen et al., 2015). PFJ load management advice should consider cumulative kinetic measures, not just peak values from individual steps. Therefore, the purpose of this study was to investigate the influence of speed on peak and cumulative PFJ force and stress in recreational runners.

METHODS: Ten male and ten female recreational runners provided written informed consent and were enrolled in the study (Table 1). Participants were required to be aged between 18 and 50 years, running at least 10 km per week, and with no running-related lower limb injury in the previous six weeks. The study was approved by the Macquarie University Human Research Ethics Committee. Participants attended two laboratory testing sessions within three weeks. In the first session, participants demographic information and running history were collected and they completed a maximal running assessment to determine $\dot{V}O_{2MAX}$ using established protocols (Tanner & Gore, 2013). In the second session, participants underwent a biomechanical evaluation on an instrumented treadmill where running kinematic and kinetics were recorded during a continuous three-minute run at four different speeds (2.5 m/s, 3.1 m/s, 3.6 m/s, 4.2 m/s). Estimations of PFJ force and stress are reported to be similar across treadmill and overground running (Willy et al., 2016).

Table 1: Participant Demographics (mean and standard deviation).

Characteristic	Male (n=10)	Female (n=10)	Total (n=20)
Age, years	34.0 ± 7.4	34.1 ± 11.9	34.0 ± 9.7
Height, m	1.74 ± 0.05	166.0 ± 0.04	1.70 ± 0.06
Mass, kg	70.4 ± 7.2	59.3 ± 5.3	64.8 ± 8.4
Weekly distance, km	57.0 ± 23.6	50.0 ± 22.9	53.3 ± 22.9
10 km race time, min	39.7 ± 3.8	46.4 ± 3.9	43.2 ± 5.1
$\dot{V}O_{2MAX}$, ml/kg/min	65.8 ± 8.6	57.3 ± 5.2	61.4 ± 8.1

An eight-camera Vicon motion capture system (250 Hz, Oxford Metrics Ltd, Oxford, UK) was used to capture 3D joint kinematics of the lower limb with synchronised ground reaction force (GRF) collected from the force-instrumented treadmill (1000 Hz, AMTI Compact Tandem, Massachusetts, US). A modified University of Western Australia full-body marker set (Chin et al., 2009) was placed on each participant on select landmarks at the head, trunk, pelvis and legs. Marker trajectories were gap-filled in Vicon NEXUS using a quintic spline method (Woltring, 1985). Data were exported to Visual 3D software (C-Motion, Inc., Maryland, USA), which was used to create a nine-segment, 3D lower extremity musculoskeletal model. Data were extracted and averaged over 24 seconds during the middle third of each three-minute run to achieve stable values (Riazati et al., 2019). Marker trajectories and GRF data were filtered using a low-pass fourth-order Butterworth filter with a matched cut-off frequency of 20 Hz (Mai & Willwacher, 2019). Gait events were determined based on vertical GRF thresholds of 50 N. Joint angles, moments, and temporospatial parameters were also determined. The net internal knee extension moment was obtained by submitting filtered kinematic and GRF to a conventional Newton-Euler inverse dynamics analysis and reported in the proximal segment coordinate system. Joint moments were normalised to body mass*height and reported in Nm/kg·m. PFJ kinetics were calculated using a biomechanical model (Brechter & Powers, 2002) that considers knee flexion angle, net knee extension moment and quadriceps moment arm and is commonly used in studies investigating PFJ stress (Bonacci et al., 2014; Wirtz et al., 2012). Cumulative PFJ force and stress were estimated from the product of total impulse per step (sum of positive and negative) and the number of strides per 1km of continuous running (500m/step length) (Willy et al., 2016). Knee kinematics, peak GRF, and instantaneous vertical loading rate (IVLR) (Futrell et al., 2018) were calculated to assist with interpretation.
Statistical analyses were performed with Jamovi (version 1.6, Sydney, Australia). The relationships between the dependent (peak and cumulative PFJ force and stress) and independent (running speed) variables were explored using linear mixed models that included speed as fixed effect and participant as a random effect. Residual plots were used to assess model assumptions. Post-hoc *t*-tests were used to determine differences between running speeds. Descriptive data were presented as group means and standard deviation (SD), and percentage differences. Effect sizes (ES) were calculated using Cohen's *d* with 0.2, 0.5, and 0.8 representing a small, medium, and large ES, respectively.

RESULTS: PFJ force and stress for each running speed are illustrated in Figure 1, with both measures significantly increasing with speed (main effect: $p<0.001$). PFJ force and stress significantly increased between the slowest speed (2.5 m/s) and the two fastest speeds (3.6 m/s: 14.8-16.2% increase, ES 0.51-0.64; 4.2 m/s: 21.8-23.8% increase, ES 0.78-0.98). There were no significant differences in PFJ force and stress between the two slowest speeds (2.5 and 3.1 m/s: 7.5-7.9% increase, ES 0.26-0.31). Estimated cumulative PFJ force and stress significantly decreased with speed (main effect: $p<0.001$). The largest decrease in cumulative measures was observed between the two slowest speeds (2.5 and 3.1 m/s), with a 16.6% (ES 0.67) and 16.8% decrease (ES 0.63) in PFJ force and PFJ stress, respectively.

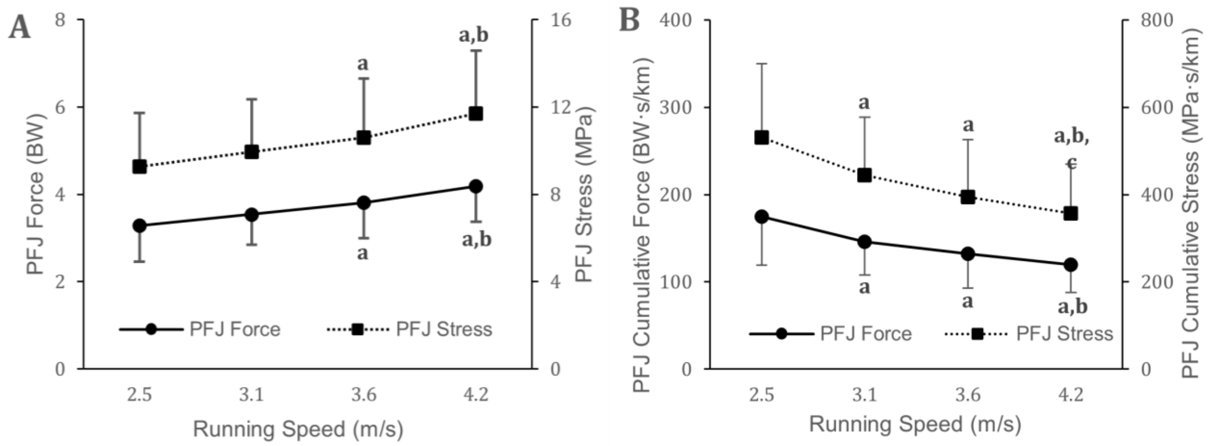

Figure 1: (A) Peak and (B) cumulative patellofemoral joint force and stress for each running speed. Abbreviations: PFJ, patellofemoral joint; BW, body weight. [a] Indicates significant difference from 2.5 m/s; [b] Indicates significant difference from 3.1 m/s; [c] Indicates significant difference from 3.6 m/s.

Spatiotemporal variables, knee kinematics, and kinetics across all running speeds are presented in Table 2. Step rate, step length, peak GRF, IVLR, and peak knee flexion during stance significantly increased with each speed increment. At faster speeds (3.6 and 4.2 m/s), knee flexion at initial contact was significantly greater than the slowest speed (2.5 m/s; 6.5-11.0% increase, ES 0.25-0.43). Additionally, peak knee extensor moment was significantly greater at faster speeds (3.6 and 4.2 m/s) compared to the slowest speed (2.5 m/s; 12.4-19.6% increase, ES 0.71-1.04).

Table 2: Spatiotemporal variables, kinematics, and kinetics for each running speed (mean ± SD)

	2.5 m/s	3.1 m/s	3.6 m/s	4.2 m/s	*p*
Step rate, steps per min	170 ± 9	175 ± 9[a]	182 ± 11[a,b]	187 ± 10[a,b,c]	<0.001
Step length, m	0.89 ± 0.05	1.05 ± 0.06[a]	1.20 ± 0.07[a,b]	1.34 ± 0.07[a,b,c]	<0.001
Peak GRF, BW	2.42 ± 0.19	2.56 ± 0.20[a]	2.64 ± 0.21[a,b]	2.69 ± 0.22[a,b,c]	<0.001
Instantaneous VLR, BW/sec	67.7 ± 14.7	83.6 ± 21.6[a]	98.9 ± 26.4[a,b]	126.0 ± 28.2[a,b,c]	<0.001
Peak knee flexion during stance, degrees	28.5 ± 7.0	30.7 ± 7.0[a]	32.8 ± 7.2[a,b]	34.7 ± 8.0[a,b,c]	<0.001
Knee flexion at IC, degrees	15.5 ± 3.6	16.0 ± 3.7	16.5 ± 4.27[a]	17.2 4.5[a,b]	<0.001
Peak knee extensor moment (Nm/kg·m)	1.05 ± 0.21	1.12 ± 0.17[a]	1.18 ± 0.18[a,b]	1.27 ± 0.17[a,b,c]	<0.001

Abbreviations: GRF, ground reaction force; BW, body weight; IC, initial contact; VLR, vertical loading rate. Superscript indicates significant difference with the following speeds: [a] 2.5 m/s; [b] 3.1 m/s; [c] 3.6 m/s.

DISCUSSION: Both peak PFJ force and stress increased with running speed, with forces of 3-4 times body weight and stresses of 9-12 MPa observed. These peak values and speed effects are consistent with previous findings (Willy et al., 2016; Wirtz et al., 2012). The increase in PFJ force and stress at faster speeds are likely explained by the greater knee extensor moment and increased peak knee flexion angle during stance observed during faster running. In contrast, cumulative PFJ force and stress significantly decreased with running speed (Figure 1). Notably, the largest decrease in cumulative PFJ measures (~17%) occurred between the slower running speeds (2.5 and 3.1 m/s), consistent with a previous study that found a 27% reduction in cumulative impulse (derived from knee joint extensor moment impulse) between 2.2 and 3.3 m/s (Petersen et al., 2015). Previous findings in high-level runners also reported no differences in weighted cumulative PFJ force at running speeds greater than 3.9 m/s (Starbuck et al., 2021), which may highlight a diminishing speed effect on cumulative PFJ measures at faster compared to slower running speeds. This study included slower running speeds that may more accurately reflect the typical training speeds of recreational runners.

Coaches and clinicians of recreational runners should consider prescribing moderate running speeds (≥3.1 m/s) with reduced training volume or an interval-based approach rather than slow-running speeds (~2.5 m/s) to manage the cumulative PFJ measures. The faster running increases the magnitude of PFJ force and stress peaks per step but results in fewer steps and less total accumulated force and stress. This may be relevant in preventing and managing overuse PFJ conditions and should be explored in prospective cohort and intervention studies. There are some limitations to this study. The PFJ model used was a simplified planar model that does not consider individual three-dimensional patella kinematics and geometry. Individual differences in patella geometry may affect PFJ contact area and stress. Additionally, the net knee extensor moment calculation used to determine PFJ force does not factor co-contraction of muscles around the knee joint and, therefore, may underestimate quadriceps force and, subsequently, PFJ force and stress. Finally, cumulative PFJ measures were determined using the total impulse of the respective PFJ force and stress curves, which assume equal weighting applied across the gait cycle. A weighted-cumulative approach that factors the magnitude of force and fatigue properties of the PFJ could be considered. However, no such method has been identified in the literature that considers these factors.

CONCLUSION: Peak PFJ force and stress per step increase but the force and stress accumulated per 1km decrease with increased running speed. Recreational runners should minimise slow speed running (2.5 m/s) if the goal is to reduce cumulative PFJ force and stress.

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