



Full length article

Patellofemoral joint stress measured across three different running techniques

Ana Flavia dos Santos^{a,b,*}, Theresa Helissa Nakagawa^c, Fábio Viadanna Serrão^a, Reed Ferber^b

^a Physical Therapy Department, Federal University of São Carlos, São Carlos, Brazil

^b Faculty of Kinesiology, University of Calgary, Calgary, Canada

^c Physical Therapy Department, North University Centre, Manaus, Brazil

ARTICLE INFO

Keywords:

Gait retraining
Biomechanics
Runners
Knee pain

ABSTRACT

Background: Patellofemoral pain (PFP) is the most common running-related injury. It has been shown in previous studies that gait retraining may have a beneficial effect on patellofemoral joint stress (PFJS).

Research question: Is there a reduction of PFJS across 4 running conditions: 1. runner's typical rearfoot strike pattern, 2. forefoot landing, 3. step rate increase by 10% and 4. forward trunk lean?

Methods: Nineteen healthy runners (28.05 ± 5.03 years; 26.58 ± 8.85 km/week, 6.00 ± 4.51 years of running experience) completed one running trial for each condition, at the same subject-specific comfortable speed on a treadmill. Kinetic and kinematic data were collected and measures of hip, knee and ankle joint moments and PFJS were calculated.

Results: Compared to rearfoot strike condition, peak PFJS and PFJS-time integral per step were significantly ($P < 0.01$) lower during forefoot landing and step rate increase conditions. PFJS per kilometer was significantly reduced for forefoot landing (17.01%; $P < 0.01$) and increased step rate (12.90%; $P = 0.003$). Forward trunk lean technique showed no significant differences in peak PFJS ($P = 0.187$), PFJS-time integral per step ($P = 0.815$) and PFJS per kilometer ($P = 0.077$) compared to rearfoot strike pattern.

Interpretation: The comparison between techniques revealed greater reductions on PFJS by forefoot landing, followed by 10% step rate increase condition. These changes were the result of different lower limb movement strategies across the 2 running conditions. We conclude that compared to a rearfoot strike pattern, both a forefoot landing and step rate increase result in lower cumulative PFJS joint stress in healthy runners, with the forefoot landing being the most effective. These running technique modifications could be recommended to reduce PFJS loads and may have implications for PFP prevention.

1. Introduction

Every year up to 79% of runners reported a musculoskeletal injury [1] and nearly 50% of all injuries involve the knee joint with patellofemoral pain (PFP) being the most common knee injury [1,2]. A chronic history of PFP could be related to patellofemoral osteoarthritis development [3]. Therefore, it is imperative to better understand the loads acting on this joint during different running techniques.

One way to analyze the forces acting on the patella is to calculate the patellofemoral joint stress (PFJS) [4]. Increased PFJS may be associated with the etiology or exacerbation of PFP symptoms due to an increase in subchondral tissue pressure [5]. The most common biomechanical model to estimate PFJS considers the subject-specific knee flexion angle and knee extensor moment [6] and this particular method has been previously used across different activities, including running

[4,7–10].

Research has shown that three different running technique modifications may promote beneficial effects on lower limb biomechanics, including PFJS reduction. Specifically, it has been shown that landing with a forefoot strike pattern results in a 10–27% reduction in peak PFJS in healthy runners [8,11,12] and a 50% reduction in PFP, concomitant with alterations in running kinematics for a group of runners experiencing PFP [7]. As well, research has shown that an increase in step rate (number of steps per minute) during running results in decreased peak PFJS by 15–20% and a reduction in PFJS per kilometer by 9–12% in both healthy runners [8] and for runners with PFP [9]. Third, running with a forward trunk lean has been shown to decrease peak PFJS by 6% in healthy runners [13]. However, several methodological limitations in these investigations should be taken into consideration.

While the aforementioned gait retraining approaches have shown

* Corresponding author at: Rod. Washington Luis, km 235, Departamento de Fisioterapia, São Carlos, SP, CEP 13565-905, Brazil.

E-mail address: santosaf@live.com (A.F. dos Santos).

positive results on PFJS, to the best of our knowledge, a comparison of these three running techniques in a single cohort has not yet been conducted. The methodological differences, especially in the mathematical model to estimate PFJS between previous studies, have to be taken into account when interpreting and comparing the results. Recently, Nunes et al. [4] in a systematic review highlighted the relevant differences in previous investigations when considering similar methods of PFJS calculation. Despite being an indirect calculation, that considers only sagittal plane forces [4], these authors suggested that a standard method for calculating PFJS should be applied within the same experimental protocol in order to help compare effects across different gait running techniques. As well, running is a high repetitive activity and it is important to investigate and understand the proximal and distal load management mechanisms necessary to reduce PFJS beyond the knee joint for each of these techniques in order to understand the changes in lower limb internal and external forces.

Therefore, the aim of this investigation was to measure changes in ground reaction forces (GRF) and lower limb kinematic and kinetic running gait patterns and thereby calculate changes in PFJS, during the following running conditions: forefoot running (FFOOT), a 10% step rate increase (STEP10%), and a forward trunk lean (FTL) as compared to a runner's typical rearfoot strike running pattern and compared between each technique. We hypothesized that FFOOT would decrease the knee extensor moment as a consequence of greater ankle joint contribution during stance phase. Second, we hypothesized that a higher cadence (STEP10%) during running would decrease peak knee flexion angle. During the FTL condition, we hypothesized that a greater contribution from the hip joint would lead to a reduced knee extensor moment. We also hypothesized that a reduction on PFJS would be greatest during the FFOOT, followed by STEP10% and FTL.

2. Methods

2.1. Participants

Nineteen recreational runners were included in the study (8 males, 11 females). A post-hoc analysis was conducted to verify that the study was powered appropriately using peak PFJS values, which resulted in power greater than 0.9 (effect size = 1.17; $\alpha = 0.05$). The inclusion criteria for participation were: striking with the rearfoot, running a minimum of 20 km/week for 3 months, absence of any lower limb injury at least 3 months prior to the assessment. The participants had the following characteristics: mean \pm SD age = 28.05 \pm 5.03 years; running training = 26.58 \pm 8.85 km/week, running experience = 6.00 \pm 4.51 years. Ethical approval was obtained from the institutional ethics review board for conducting the study and all participants provided written informed consent to participate.

2.2. Procedures

Prior to data collection, all runners were videotaped using a high speed camera (120 Hz) while running on a treadmill, without any instruction, to determine foot strike pattern and preferred step rate and running speed [15]. The preferred speed was determined by each runner and did not change between running conditions. Next, each participant performed the 3 running techniques, in randomized order, to become accommodated to the experimental conditions. Verbal instructions [16] were given to the participants to ensure the correct execution of each technique. Briefly, for FFOOT, runners were asked to "strike with the forefoot", touching the ground with the metatarsal joints, and rearfoot contact after foot strike was optional. For STEP10%, runners were instructed to keep the higher cadence controlled by a digital audio metronome [15,16] and for FTL, the runners were asked to "run with an increase in flexed trunk posture", which was confirmed by visual inspection [16,18]. In order to isolate the effects of each technique and to ensure no overlap between the techniques, foot strike

pattern, step rate cadence and trunk flexion angle were controlled in each opposing condition by verbal instruction and visual confirmation from the examiner. A pilot study was conducted prior to data collection and demonstrated that the visual inspection method was reliable. Each technique was performed correctly for 2 min, separated by 2 min of rest (walking at 1.38 m/s), at each participant's self-selected running speed.

Following the training sessions, but no more than three days later, ground reaction force (GRF) kinetic data (1000 Hz; Bertec instrumented treadmill, Columbus, OH, USA) and kinematic data (200 Hz; 7-camera VICON MX3 Motion System, Oxford, UK) were collected. Anatomical and tracking reflective markers were placed on each participant [16]. To ensure acclimation to the treadmill, the second running session started with a warm-up consisting of 5 min walking at 1.38 m/s followed by a randomized order of running conditions established during the first running session. After the correct execution and maintenance of each running technique for 1 min [15], 30 s of GRF and kinematic data were collected.

2.3. Data analysis

2.3.1. Kinematics and kinetics

The average of 10 successive strides was analyzed for each running condition from the dominant limb of each runner. Visual 3D software (C-Motion Inc., Rockville, USA) was used to calculate anatomical joint coordinate systems, filter marker trajectory, and filter GRF raw data (4th-order, zero-lag, low-pass Butterworth at 12 Hz and 25 Hz, respectively). The net internal joint moments were determined using a standard inverse dynamics approach wherein joint moment data were normalized by body mass and reported in units of Nm.kg⁻¹. The Cardan angles were calculated using the joint coordinate system definitions recommended by the International Society of Biomechanics [19] relative to the static standing trial. Using a custom Matlab (MathWorks Inc., Natick, USA) algorithm, the foot strike and the toe off events were identified when the vertical GRF crossed a 20 N threshold level. The foot strike pattern between the conditions was cross-validated according to the foot strike angle with respect to the ground in the sagittal plane (a positive value indicated dorsiflexion) [20]. The step length was estimated by multiplying the constant velocity per stance phase duration, which was followed by the estimation of the number of steps required to run 1 km.

2.3.1.1. PFJS. PFJS was calculated using a previously described model [6,21], which has been applied in previous running investigations [22]. The model considers the subject specific knee flexion angle (x) and net joint moment (M_k) data during the stance phase of running as input variables. The quadriceps muscle effective lever arm (L_Q) was calculated as a function of knee flexion angle (x) using the nonlinear equation reported by van Eijden et al. [23] from a cadaveric study (Eq. (1)):

$$L_Q = 0.00008x^3 - 0.013x^2 + 0.28x + 0.046 \quad (1)$$

The quadriceps force (F_Q) was obtained as follows (Eq. (2)):

$$F_Q = Mk/L_Q \quad (2)$$

The patellofemoral joint compression force (PFCF) was estimated as the product of the F_Q and a constant (k) (Eq. (3)):

$$PFCF = F_Q \cdot k \quad (3)$$

The constant k was determined using a nonlinear equation [23] (Eq. (4)):

$$k(x) = (0.462 + 0.00147x - 0.0000384x^2) / (1 - 0.0162x + 0.000155x^2 - 0.00000698x^3) \quad (4)$$

The patellofemoral contact area (CA) was determined relative to knee flexion angle (x) [24] (Eq. (5)):

$$CA = 0.00002x^4 - 0.0033x^3 + 0.1099x^2 + 3.5273x + 81.058 \quad (5)$$

The PFCF was divided by the CA to estimate the PFJS (Eq. (6)).

$$PFJS = PFCF/CA \quad (6)$$

The peak PFJS and PFJS-time integral during the stance phase of running were the primary variables of interest related to the PFJ kinetics. The cumulative trapezoidal numerical integration was used to calculate the PFJS-time integral. Considering that the increased step rate running technique involved a higher number of steps per kilometer, the cumulative PFJS over the distance of 1 km was estimated by multiplying the average cumulative PFJS from 10 steps by the number of steps required to run the 1 km distance.

2.4. Statistical analysis

Trunk and lower limb joint angles in the sagittal plane, lower limb joint internal moments, peak PFJS, PFJS-time integral and spatio-temporal data were compared between the runner's typical rearfoot running technique and across the 3 alternate running techniques (4 levels) using a repeated measures analysis of variance (ANOVA) with polynomial contrasts. Bonferroni adjust was used and α level set at 5% for significant differences. Effect sizes were determined using generalized eta-squared (η_p^2) [25] and all values were greater than 0.27 which are considered to be a large effect sizes.

3. Results

The average running velocity was 2.81 ± 0.27 m/s. There were significant differences across running techniques and no overlap between the three conditions was verified (Table 1). The analysis of the footstrike angle revealed a plantar flexion angulation during FFOOT. The footstrike angle was significantly different ($P < 0.01$) for FFOOT as compared to preferred rearfoot running, STEP10% and FTL. While, the footstrike angle was significantly different during STEP10% ($P = 0.046$) and FTL ($P = 0.012$) as compared to preferred rearfoot running, the runners still exhibited a dorsiflexed footstrike angle during both of these conditions, which represents a rearfoot strike according to Altman and Davis [20].

The running cadence was controlled during all conditions by audio feedback, hence, the 10% rate increase showed a greater number of steps compared to rearfoot running, FFOOT and FTL ($P < 0.01$). The FFOOT ($P = 0.09$) and FTL ($P = 1.00$) did not alter the number of steps per minute compared to the rearfoot running. There was a 7.89 degree increase in trunk flexion angle during FTL compared to preferred running ($P < 0.01$), no difference in this angulation during FFOOT and STEP10% ($P = 1.00$). The trunk sagittal angle during FTL was also greater compared to FFOOT and STEP10% techniques ($P < 0.01$).

The effects of each running condition on PFJS and lower limb biomechanical variables are reported in Table 2 and there were significant differences for the different running technique (Wilks' $\lambda = 0.002$; $F(42, 122.391) = 19.602$; $p = .000$). Compared to the typical rearfoot strike condition, FFOOT resulted in a significant 27.09% reduction in peak

Table 1
Mean (SD) kinematic and spatiotemporal variables for each running condition.

	Typical rearfoot strike	Forefoot landing	10% step rate increase	Forward trunk lean
Footstrike angle (degrees) plantar(-)/ dorsiflexion(+)	14.53 (3.72)	-6.85 (3.86) [*]	12.20 (4.61) ^{*,α}	16.11 (3.81) ^{*,α,\S}
Step length (m)	0.74 (0.06)	0.69 (0.05) [†]	0.67 (0.13) [†]	0.76 (0.07) ^{α,\S}
Step rate (steps·minute ⁻¹)	172.63 (9.82)	174.11 (9.92)	188.63 (11.10) ^{*,α,\S}	173.05 (9.78)
Trunk flexion angle (degrees)	5.36 (3.90)	4.99 (3.24)	5.55 (5.51)	13.25 (3.78) ^{*,α,\S}

^{*} Significantly different from rearfoot strike (preferred running) ($p < 0.05$).

^{α} Significantly different from forefoot ($p < 0.05$).

^{\S} Significantly different from 10% step rate increase ($p < 0.05$).

PFJS ($P < 0.01$) (Fig. 1), along with a significant reduction in PFJS-time integral per step ($P < 0.01$) and PFJS-time integral estimation per kilometer ($P < 0.01$). The FFOOT also resulted in a 36.73% greater plantarflexion moment ($P < 0.01$), along with significantly lower peak knee flexion angle ($P = 0.01$), and a lower knee extensor moment ($P < 0.01$) as compared to the rearfoot strike pattern. The peak vertical GRF (Fig. 2) also significantly increased by 9.33% ($P < 0.01$) compared to the rearfoot strike condition.

The STEP10% resulted in an 11.78% reduction in peak PFJS ($P < 0.01$) and also a significant reduction in PFJS-time integral per step ($P < 0.01$) and PFJS-time integral accumulated per kilometer ($P = 0.003$). No change in knee extensor moment ($P = 1.00$) was measured despite a significant reduction in the knee flexion angle ($P < 0.01$) as compared to the rearfoot strike condition.

For FTL, peak knee flexion angle was 1.76° greater ($P = 0.022$) compared to the typical rearfoot pattern. Although peak PFJS was reduced by 4.73%, it did not reach statistical significance ($P = 0.187$) and no statistical significance was found for PFJS-time integral estimation per kilometer ($P = 0.815$). A significant 64.70% increase in hip extensor moment ($P < 0.01$) was also observed during this technique as compared to the rearfoot strike condition.

The pairwise comparison between techniques showed significant differences for PFJS. FFOOT exhibited lower peak PFJS compared to STEP10% ($P = 0.003$), FTL showed greater peak PFJS, PFJS-time integral and PFJS-time integral per kilometer compared to FFOOT ($P < 0.01$; $P < 0.01$; $P = 0.08$) and STEP10% ($P = 0.014$; $P < 0.01$; $P = 0.05$).

4. Discussion

Gait retraining is becoming a common option in a clinical settings in order to improve lower limb running biomechanics [26]. Previous studies have shown that FFOOT, STEP10% and FTL all improve lower limb biomechanics, particularly with respect to patellofemoral kinetics [7–9,11–13]. However, to the best of our knowledge, no study had evaluated the effects of different running technique conditions in a single experiment. Thus, the aim of this investigation was to measure changes in lower limb kinematic and kinetic running gait patterns and thereby calculate changes in PFJS, during these running conditions, as compared to a runner's typical rearfoot strike running pattern.

Overall, and in support of our hypotheses, changes in running gait patterns resulted in reductions in peak PFJS and PFJS-time integral per step as compared to a runner's typical rearfoot strike pattern, with the FFOOT being the most effective condition. However, contrary to our hypotheses, the FTL condition presented no significant reduction on PFJS variables evaluated in the current study.

Running represents a highly repetitive biomechanical pattern, with an estimation of more than 1 thousand steps for every 6 min of running [16]. Considering the repetitive nature of distance running, the cumulative PFJS estimation over a greater distance could be directly related to the potential for injury. Therefore, a significant strength of the current study is that, to our knowledge, this is the first study to investigate the biomechanical changes associated with commonly used gait retraining methods in a single cohort of experienced healthy runners.

Table 2
Mean (SD) PFJS and biomechanical variables for each running condition.

	Rearfoot strike	Forefoot landing	10% step rate increase	Forward trunk lean
Peak PFJS stance phase (MPa)	8.23 (2.32)	6.00 (2.71) [*]	7.26 (2.16) ^{*,α}	7.84 (2.31) ^{α,§}
PFJS-time integral (MPa s)	0.86 (0.27)	0.67 (0.30) [*]	0.70 (0.21) [*]	0.84 (0.27) ^{α,§}
PFJS-time integral/km (MPa s)	576.93 (158.83)	478.76 (197.66) [*]	502.48 (137.08) [*]	548.84 (161.06) ^α
Number of steps per km	676.85 (60.28)	722.97 (63.40) [†]	722.73 (68.15) [†]	660.20 (60.49) ^{α,§}
Peak knee flexion angle stance phase (degrees)	40.33 (5.04)	37.48 (5.81) [†]	37.50 (4.03) [†]	42.09 (4.28) ^{*,α,§}
Peak knee extensor moment stance phase (N m kg ⁻¹)	1.62 (0.36)	1.19 (0.47) [†]	1.55 (0.25) ^α	1.55 (0.32) ^α
Plantarflexion moment stance phase (N m kg ⁻¹)	1.47 (0.16)	2.01 (0.20) [†]	1.48 (0.17) ^α	1.46 (0.17) ^α
Hip extensor moment stance phase (N m kg ⁻¹)	0.34 (0.15)	0.38 (0.19)	0.31 (0.17)	0.56 (0.15) ^{*,α,§}
Peak GRF (body weight)	2.25 (0.15)	2.46 (0.19) [*]	2.18 (0.43) ^α	2.19 (0.14) ^α

* Significantly different from rearfoot strike (preferred running) ($p < 0.05$).

^α Significantly different from forefoot ($p < 0.05$).

[§] Significantly different from 10% step rate increase ($p < 0.05$).

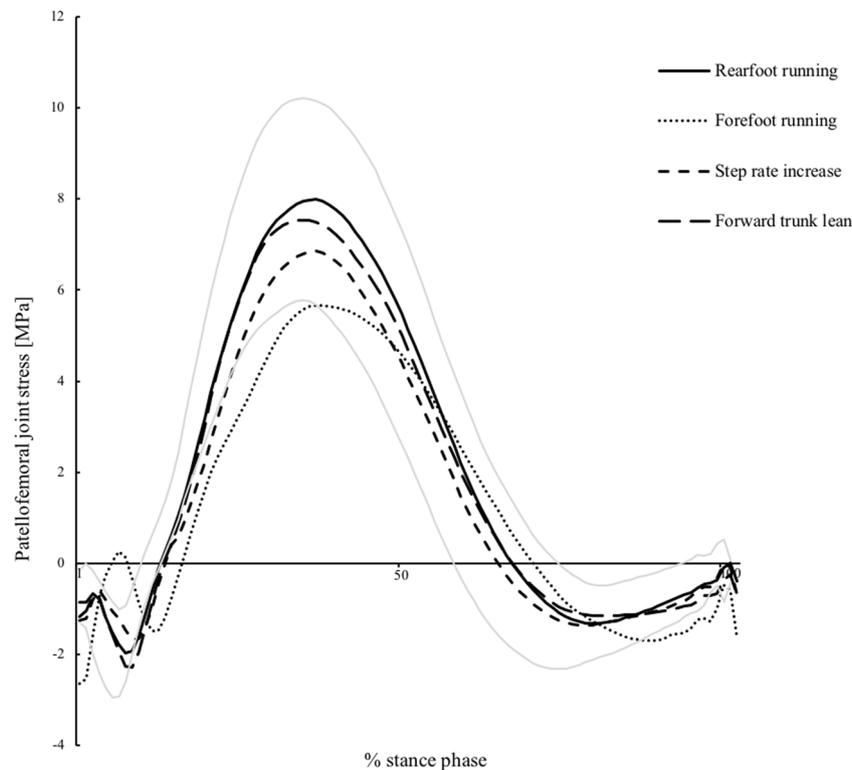


Fig. 1. Patellofemoral joint stress during the stance phase of each running condition. The grey lines represent \pm SD for the typical rearfoot strike running.

Overall the results showed that FFOOT and STEP10% techniques can reduce the PFJS, however, the changes in PFJS are the result of different kinetic and kinematic lower limb mechanisms in order to achieve this result.

In support of our hypothesis, the FFOOT resulted in a greater plantarflexor moment ($P < 0.01$) during the stance phase of running gait as compared to rearfoot running. During the first portion of stance phase, this gait pattern results in the center of pressure moving more anterior to the ankle joint resulting in greater plantarflexor muscle force to control the dorsiflexion moment resulting from the GRF [27]. Moreover, FFOOT resulted in a 2.85 degree reduction in peak knee flexion angle (Fig. 3), which is directly related to the PFJS model calculation. The higher contribution of the ankle joint to absorb and dissipate the greater GRF during the first half of stance phase was also reported by Williams et al. [28]. Moreover, along with the lower peak knee flexion angle, these results could explain the 26.54% reduction in knee extensor moment (Fig. 4). The FFOOT technique also resulted in the lowest peak PFJS compared to rearfoot running and these results are in agreement with previous studies [12,14] suggesting that landing with the forefoot can attenuate the impact transient of the GRF [27].

However, this landing pattern increases tibial acceleration during initial contact [29] and subsequently results in greater peak vertical GRF (Fig. 2). The results of the current study also show that this landing pattern reduces the step length by 5 cm and the stance phase time by 0.02 s compared to a rearfoot footstrike pattern. Finally, it is possible that the runners may have adopted a higher center of mass vertical displacement during forefoot landing, which may serve to explain the 9.33% increase in the active peak vertical GRF, similar to previous results [12,14].

When running with a 10% higher cadence, runners exhibited a significant reduction in step length and concomitantly placed their foot closer to the body's center of mass projection at initial contact [15]. These changes in gait mechanics could explain the 2.83 degree reduction in peak knee flexion angle during the STEP10% condition, compared to rearfoot running. However, these results are contrary to Willson et al. [9], who did not show a significant reduction in the peak knee extensor moment when runners increased their cadence. Regardless, based on the model used to calculate PFJS, the reduction in peak knee flexion was enough to significantly reduce the peak PFJS and consequently, reduce the PFJS-time integral per step and a result in a

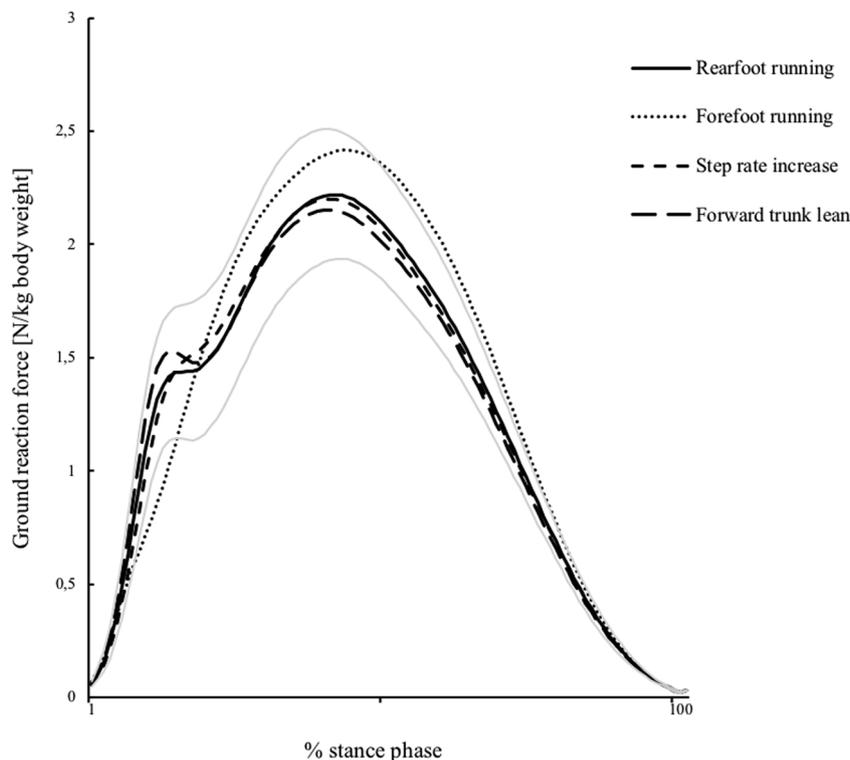


Fig. 2. Vertical ground reaction forces during the stance phase of each running condition. The grey lines represent \pm SD for the typical rearfoot strike running.

12.90% reduction in PFJS-time per kilometer.

The FTL resulted in an increase in the hip extensor moment and an increase in peak knee flexion angle (Fig. 3), thereby resulting in lower PFJS as compared to the rearfoot strike condition, but these results did not approach significance. Also, the forward trunk lean condition resulted in a 4.74% reduced peak PFJS compared to rearfoot running but these results are disparate to those of Teng and Powers, who reported a 6.04% reduction [13]. Interestingly, an increase in forward trunk, and the aforementioned changes in the hip extensor moment, resulted in small reductions PFJS, albeit non-significant. Therefore, future research is necessary to expand the PFJS model and potentially include other factors, such as hip extensor moment, in order to better understand

these confounding results.

Although the relevant PFJS reductions were obtained across the three running techniques based on only simple verbal instructions, distal and proximal joint contributions must be considered during the execution of each technique. The results of the present study showed there was a 36.73% increase in the ankle plantarflexion moment during FFOOT and these results are supported by Vannatta and Kernozek [14] who also reported an increase of 12% in average gastrocnemius force and 29% greater soleus force during the stance phase of forefoot running. Additionally, during FTL, the average hip extensor moment increased by 64,70%. Therefore, future prospective studies are necessary to better understand the long-term consequences of gait retraining in an

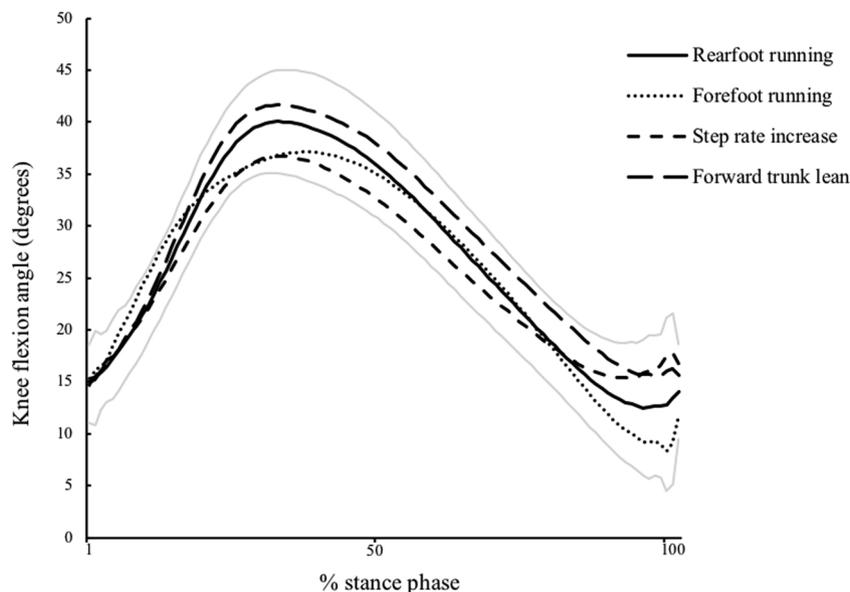


Fig. 3. Knee flexion angle during the stance phase of each running condition. The grey lines represent \pm SD for the typical rearfoot strike running.

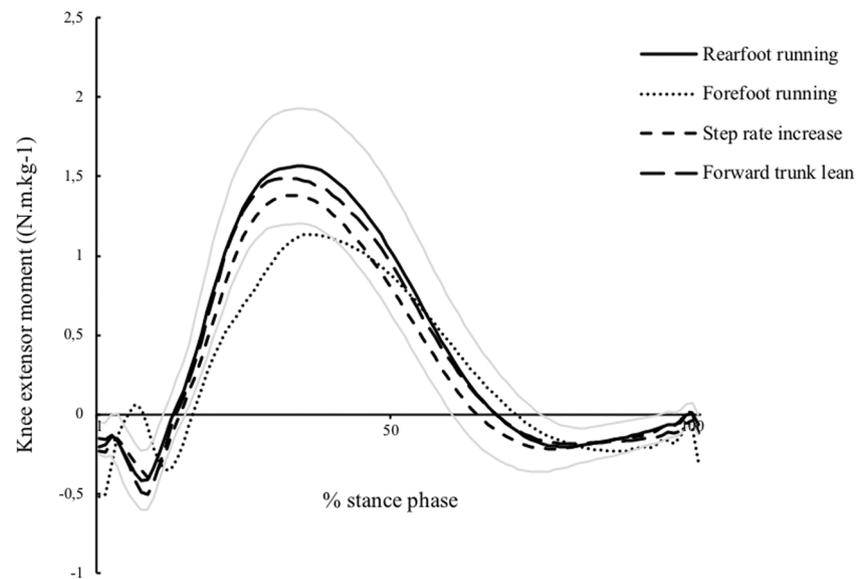


Fig. 4. Knee extensor moment during the stance phase of each running condition. The gray lines represent \pm SD for the typical rearfoot strike running.

effort to reduce PFJS.

A comparison across the three techniques showed that the FFOOT was the most effective running condition for reducing patellofemoral joint loading (Fig. 1) and reduced peak PFJS by 17.35% compared to the STEP10% technique, followed next by 23.46% compared to FTL. As well the FFOOT technique resulted in an 8.44% reduction in PFJS-time integral per kilometer compared to the forward trunk lean condition. This information could be practical and useful for clinicians, coaches and athletes in order to choose the best technique by considering the effectiveness of each condition and the runner's previous injury history.

Limitations need to be considered when interpreting the results. Although the biomechanical model used to estimate the PFJS was based on previous studies [6,21], the model is two-dimensional, and neither frontal nor transverse plane kinematics or kinetics were considered [4]. As well, the patellofemoral contact area (CA) was estimated based on a previous study [24] and hamstrings-quadriceps muscle co-contraction was not taken into account, thereby resulting in the quadriceps force estimation potentially being underestimated. However, we believe that this limitation did not significantly influence the pairwise comparisons. Moreover, a recent systematic review reported that even more complex PFJS models, including different methods to adjust sagittal plane forces and even taking into consideration cross-sectional area or electromyographical data of knee flexor muscles, produce similar results [4]. In addition, this review [4] also concluded that “methods which use data from their own participants for most parts of the calculation might be preferred to minimize potential errors.” Thus, the current study builds upon previous research and a significant strength was that different running techniques were assessed within a single study using subject-specific PFJS models. Another limitation could be that only the immediate effects were analyzed for a group of healthy individuals. Thus, a long-term analysis involving individuals with PFP are necessary to confirm or refute the overall beneficial effect of changes in running technique on PFJS. Finally, the protocol was performed on a treadmill, limiting the interpretation of results to overground running.

5. Conclusion

FFOOT and STEP10% techniques were shown to reduce PFJS in healthy runners with a forefoot strike pattern showing the greatest reductions. Concomitant increases in the plantar flexion moment during the FFOOT and an increased hip extensor moment during FTL were also observed. These techniques could be recommended for short-term PFP rehabilitation and prevention programs but caution should be taken

with respect to proximal and distal joint overload as well as acknowledging that the long-term consequences of changing running gait biomechanics are not fully understood.

Disclosure of conflict of interest

Authors declare no conflict of interests.

Acknowledgements

The authors are grateful to São Paulo Research Foundation (FAPESP), Brazil, grants no: 2015/20306-2 and 2013/26318-7 for providing the financial support for this study. Funding was also provided through a Discovery Grant (Grant no: 1028495) and Accelerator Award (Award no: 1030390) through the Natural Sciences and Engineering Research Council of Canada (NSERC).

References

- [1] R.N. Van Gent, D. Siem, M. Van Middelkoop, A.G. Van Os, S.M.A. Bierma-Zeinstra, B.W. Koes, Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review, *Br. J. Sports Med.* 41 (2007) 469–480, <https://doi.org/10.1136/bjsm.2006.033548>.
- [2] J.E. Tauton, A retrospective case-control analysis of 2002 running injuries, *Sport. Med.* (2002) 95–102.
- [3] M.R. Utting, G. Davies, J.H. Newman, Is anterior knee pain a predisposing factor to patellofemoral osteoarthritis? *Knee.* 12 (2005) 362–365, <https://doi.org/10.1016/j.knee.2004.12.006>.
- [4] G.S. Nunes, R. Scattone Silva, A.F. dos Santos, R.A.S. Fernandes, F.V. Serrão, M. de Noronha, Methods to assess patellofemoral joint stress: a systematic review, *Gait Posture* 61 (2018) 188–196, <https://doi.org/10.1016/j.gaitpost.2017.12.018>.
- [5] J.P. Fulkerson, K.P. Shea, Mechanical basis for patellofemoral pain and cartilage breakdown, in: J.W. Ewing (Ed.), *Articul. Cartil. Knee Jt. Funct. Basic Sci. Arthrosc. Raven Press, New York, 1990*, pp. 93–101.
- [6] J.H. Brechter, C.M. Powers, Patellofemoral stress during walking in persons with and without patellofemoral pain, *Med. Sci. Sport. Exerc.* 34 (2002) 1582–1593, <https://doi.org/10.1249/01.MSS.0000035990.28354.c6>.
- [7] J.L. Roper, E.M. Harding, D. Doerfler, J.G. Dexter, L. Kravitz, J.S. Dufek, C.M. Mermier, The effects of gait retraining in runners with patellofemoral pain: a randomized trial, *Clin. Biomech.* 35 (2016) 14–22, <https://doi.org/10.1016/j.clinbiomech.2016.03.010>.
- [8] J.D. Willson, O.M. Ratcliff, S.A. Meardon, R.W. Willy, Influence of step length and landing pattern on patellofemoral joint kinetics during running, *Scand. J. Med. Sci. Sports* 25 (2015) 736–743, <https://doi.org/10.1111/sms.12383>.
- [9] J.D. Willson, R. Sharpee, S.A. Meardon, T.W. Kernozek, Effects of step length on patellofemoral joint stress in female runners with and without patellofemoral pain, *Clin. Biomech.* 29 (2014) 243–247, <https://doi.org/10.1016/j.clinbiomech.2013.12.016>.
- [10] J. Bonacci, B. Vicenzino, W. Spratford, P. Collins, Take your shoes off to reduce patellofemoral joint stress during running, *Br. J. Sports Med.* 0 (2013) 1–5, <https://doi.org/10.1136/bjsm.2013.028354>.

