The Effects of Forefoot Striking, Increasing Step Rate, and Forward Trunk Lean Running on Trunk and Lower Limb Kinematics and Comfort

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Key words
- running pattern
- forefoot strike landing
- step rate
- forward trunk lean

Abstract

This study aimed to compare the immediate effects of 3 running technique modifications on the ankle, knee, hip and trunk kinematics and on the perceived comfort in healthy runners. The modifications were: forefoot striking pattern (FFOOT); increasing 10% of step rate (10% SR); and increasing forward trunk lean (FTL). 31 healthy runners participated. 3-dimensional lower limb and trunk kinematics were quantified while performing each condition on a treadmill. At initial contact, the FFOOT showed an increase in plantar flexion and knee external rotation, and reduction in knee flexion and adduction. During the stance phase, this condition showed greater peak knee external rotation and less mean and peak dorsiflexion and knee flexion. The 10% SR resulted in less hip flexion at initial contact. During the stance phase this technique showed less mean and peak knee flexion, peak reduction for dorsiflexion, knee abduction, hip flexion and hip adduction. At initial contact and during the stance phase, the FTL caused greater knee adduction and hip flexion. The usual running was the most comfortable technique. The techniques showed different lower limb kinematic modifications; which could potentially reduce knee injury risk. This knowledge is clinically relevant as it can be used to better prescribe techniques in prevention and rehabilitation programs.

Introduction

The number of runners has grown significantly in recent decades [33]. It is estimated that approximately 38 million Americans run regularly [22]. This sport has the potential risk of injury that comes with the activity growth at recreational and competitive levels. The incidence of musculoskeletal injuries ranges from 19.4 to 92.4% [33]. The knee is the most affected anatomic site [33], and patellofemoral pain (PFP) is the most common dysfunction in this joint (prevalence ranging from 7.4 to 15.6%) [19].

Associated with the growth in the popularity of running, there has been an increase in the interest of investigating the factors associated with running injuries [12]. In addition to training errors, changes in the joint kinematics of the lower limb, have been associated with running-related injuries, including PFP. In recent years, it has been hypothesized that certain running technique modifications might promote beneficial effects on the lower limb biomechanics, including the forefoot striking pattern (FFOOT) [3, 15, 18, 30], the 10% step rate increase (10% SR) [11, 17, 34] and increasing forward trunk lean (FTL) [32].

Although more than 93% of distance runners are rearfoot strikers (RFS) [16], this strike pattern is suggested to be related to an increased risk of running injury [3, 8] while the forefoot strike pattern (FFS) is related to a decreased risk of running injury [5, 30]. A higher peak impact and loading rate during running are associated with lower limb injuries [25, 26], such as PFP [6]. During FFS running, some studies verified vertical impact force attenuation [3, 8, 18, 30] and patellofemoral joint stress (PFJS) reduction [2, 15]. Furthermore, the sagittal plane movement during weight bearing activities influences the PFJS [27]. Healthy runners showed less peak knee flexion during the stance phase of FFS running, which reduced the magnitude of patellofemoral joint contact force in 16%, and consequently, the PFJS [15].

Heiderscheit et al. [11] related that a 10% increase in step rate causes a 34% reduction of knee energy absorption and reduces the peak knee flexion, knee extension moment and peak hip

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adduction during landing. Furthermore, recent studies verified that 10% SR can reduce the patellofemoral joint force in healthy runners 14% [17] and reduce the PFJS in runners with PFP up to 22% [34]. In the sagittal plane, greater peak knee flexion angle increases the knee extensor moment and can be directly related to higher PFJS during landing [17]. Changes in lower limb joint kinematics in the frontal and transverse plane, such as excessive dynamic knee valgus [23], hip internal rotation [36] and hip adduction [23] during the stance phase of running, can increase the lateral patellofemoral stress [13,23,28].

It has been hypothesized that the sagittal plane trunk posture can affect the PFJS [32]. The trunk is responsible for over half of the body weight, and the increased trunk flexion results in a forward movement of the body's center of mass, resulting in a decrease in the knee extensor moment and a reduction in the PFJS [29]. In fact, Teng et al. [32] found that a slight forward trunk lean increase during running causes reduction in the PFJS. The forward shift of the ground reaction force vector reduced knee extensor moment and generates greater demand on hip extensors [29].

No studies, to our knowledge, had reported the effects of the cited 3 running techniques on 3-dimensional kinematics of the ankle, knee, hip and trunk. In the clinical setting, due to the high cost of the instrumented treadmill of force plates, the running kinetic pattern assessment is limited. On the other hand, the kinematic assessment by a 3D or 2D motion capture system or visual inspection could be a simple and cost-effective alternative method to diagnose and provide feedback during running-related injuries rehabilitation. Previous studies have reported that managing the body's kinematic alignment during a clinical rehabilitation program is commonly used and is effective in pain and symptoms improvement [24,35]. Furthermore, the perceived runner's comfort has not been measured in these conditions. It is important as it can directly influence the athlete's adherence to the different running techniques during training or treatment.

The purposes of this study were to analyze the lower limb and trunk angles at initial contact (IC) and during the stance phase at usual running (USRUN) when compared to the 3 techniques and to the perceived runner's comfort. It was hypothesized that the running technique modifications would result in less knee abduction and external rotation and reduction of the hip adduction and internal rotation. Second, we expected greater ankle and knee kinematics changes in FFOOT and 10% SR running, with greater hip and trunk kinematic alterations at TFL in the sagittal plane. We also hypothesized that the comfort perception would be greater during USRUN.

Methods

31 recreational runners (11 females, 20 males) (▶ **Table 1**) participated in this study. An *a priori* sample size was calculated on the basis of hip adduction [11] (using $\alpha=0.05$, $\beta=0.20$). Noehren et al. [23] reported that female runners who developed PFP exhibited significantly greater hip adduction. It was revealed that 29 participants were required to adequately power the study. They were evaluated according the following criteria: aged between 18–35 years, RFS and ran a minimum of 20 km/wk at least 3 months. Subjects were excluded if they had bone, joint or ligament injury in the prior 3 months, lower limb surgery, or pain in the lower limb or trunk while running. All participants provided informed consent as approved by the University Ethics Committee for Human Investigations. All research methodology described below met the ethical standards of the International Journal of Sports Medicine [10].

The protocol was composed of 2 sessions separated by 3 days: a familiarization (session 1) and an evaluation session (session 2). In the first session, they were instructed to start running at a comfortable speed (USRUN) on a treadmill for 2 min, the preferred speed was determined by the volunteer. The step rate was visually determined by counting the number of right foot strikes and multiplying by 4 over a 30-s period [11]. The RFS pattern was confirmed by the real-time visual analysis of plantar pressure distribution using insole sensors (Novel, Munich, Germany) operating at 100 Hz. A neutral running shoe (Asics Gel-Equation 5, ASICS, Kobe, Japan) was provided for all the runners. The order of the 3 running techniques was randomized. For the FFOOT, runners were asked to "strike with the forefoot, below the metatarsal joints and the rearfoot can or not touch after" (toe-heel-toe running) [5]. The landing pattern was verified by Pedar-System real-time visual analysis. The 10% SR was controlled by a digital audio metronome [4,11]. For the FTL, the participants were verbally stimulated to run with an increase in flexed trunk posture, confirmed by visual inspection [32]. Each technique was performed correctly for a minimum of 1 min separated by 2 min of rest (walking at $1.38\,m.s^{-1}$). The velocity established during USRUN was not altered in the 3 conditions.

The kinematic data and comfort perception were collected during session 2. The dominant lower limb (5 left, 26 right) and trunk kinematics were recorded at 240 Hz using a passive 6-camera motion capture system (Qualisys, Qualisys Inc., Gothenburg, Sweden). 20 reflective markers located on anatomical landmarks and 5 cluster tracking markers were placed on each participant. The order of running techniques execution followed the random order established during session 1. The USRUN was the first technique performed in both sessions to limit the potential "memory effect" of some conditions [8,20]. After the correct execution and maintenance of each running technique for 1 min, 30-s samplings of data were performed.

A visual analog scale (VAS) was used to assess the subjective comfort after each condition, including the USRUN. The runners were familiarized with the VAS in the familiarization session and the data was collected immediately after each running technique execution during the rest period. The left end was labeled 'not comfortable' (comfort rating 0) and the right end 'very comfortable' (comfort rating 10) [21].

All the kinematic data were analyzed at IC and during the stance phase (average and peak angles). The IC was identified by a minimum vertical position of the distal heel marker [7] for the RFS conditions and a minimum vertical velocity of the distal phalange marker of the second metatarsal for FFS conditions [14]. The toe-off was determined by the second knee extension peak [7]. The average of 10 successive strides was analyzed during

Table 1 Subjects' demographics.

Age (years)	Body mass (kg)	Height (m)	Average running distance (km/week)	Running experience (years)
27.67 (5.43)	72.05 (13.61)	1.73 (0.09)	35.70 (18.25)	4.13 (4.02)

each step condition. The Cardan angles were calculated using the joint coordinate system definitions recommended by the International Society of Biomechanics [37] relative to the static standing trial using the Visual 3D software (C-Motion Inc, Rockville, USA). The kinematic data were filtered using a 4th-order, zero-lag, low-pass Butterworth filter at 12 Hz. The joint positions were determined using Matlab software (version 2008; MathWorks Inc., Natick, USA). The reporting gait recommendations were followed [31]. The kinematic variables of interest were: plantar/dorsiflexion; knee flexion, adduction/abduction and external rotation; hip flexion, adduction and internal rotation; and trunk flexion.

Statistical analyses were made using SPSS version 17.0 (SPSS Inc, Chicago, USA). Descriptive values were analyzed with respect to their statistical distribution and sphericity using the Shapiro-Wilk and Mauchly's tests. The kinematic data were compared between the USRUN and the 3 running techniques, and between techniques using a multivariate analysis of variance (MANOVA) with repeated measures. Univariate tests were conducted as follow-up tests on each dependent variable. Analysis of variance (one-way ANOVA) with repeated measures and Bonferroni correction was used to detect a significant difference between the overall comfort ratings. The significance level for all analyses was set at 0.05.

Results

The values of the preferred running speed ($2.67 \pm 0.39\,m.s^{-1}$) and step rate (167.35 ± 7.08 steps per minute) were obtained during the session 1. The kinematics results are reported in **Table 2** for each running condition. For 10% SR, there was a 10% increase in the number of steps obtained in session 1 (183.58 ± 7.55 steps per minute; $p < 0.001$). No differences were present in the step rate at FFOOT (169.03 ± 8.26; $p = 181$) and FTL (168.00 ± 7.37; $p = 1.00$) techniques compared to USRUN.

The MANOVA identified significant differences for the running technique for IC (Wilks' $\lambda = 0.008$; $F = 35.18$; $p < 0.001$), average during the stance phase (Wilks' $\lambda = 0.007$; $F = 42.67$; $p < 0.001$) and peak during the stance phase (Wilks' $\lambda = 0.023$; $F = 12.50$; $p = 0.001$). The follow-up univariate tests compared each running technique to USRUN.

Compared to USRUN at IC, the FFOOT demonstrated reduction in knee flexion ($p < 0.001$) and in knee adduction angle ($p = 0.013$), in addition to greater plantar flexion ($p < 0.001$) and knee external rotation ($p < 0.001$). The dorsiflexion ($p < 0.001$) and knee flexion ($p = 0.002$) averages during the stance phase were lower after the strike pattern modification. Peak dorsiflexion ($p < 0.001$) and peak knee flexion ($p = 0.006$) during FFOOT stance phase were reduced, while peak knee external rotation ($p < 0.001$) increased.

The 10% SR showed lower hip flexion ($p = 0.008$) at IC and lower mean knee flexion ($p = 0.003$) during the stance phase. The peak of dorsiflexion ($p < 0.001$), knee flexion ($p < 0.001$), knee abduction ($p < 0.001$), hip flexion ($p < 0.001$) and hip adduction ($p = 0.009$) were lower after higher step frequency.

The 6.19° increase in trunk flexion at IC (FTL technique) resulted in lower dorsiflexion ($p = 0.015$), greater knee adduction ($p = 0.031$) and hip flexion ($p < 0.001$). The 6.07° increase in trunk flexion during the stance phase resulted in greater mean knee adduction and lower peak knee abduction ($p < 0.001$; $p < 0.001$, respectively), and lower mean and peak hip flexion ($p < 0.001$; $p < 0.001$, respectively). The peak of trunk flexion during the stance phase was 6.57° higher than USRUN ($p < 0.001$).

The pairwise comparisons between techniques showed greater plantar flexion angle during the FFOOT compared to the other techniques at IC ($p < 0.001$) and FTL showed greater dorsiflexion peak during the stance phase ($p < 0.001$). For all analyses, the trunk forward lean was different between the FTL and other techniques ($p < 0.001$). The differences in the frontal plane had occurred just for the knee joint. The FTL showed greater knee adduction at IC compared to other techniques ($p < 0.001$, $p = 0.040$) and, during the stance phase the 10% SR demonstrated less knee adduction than FFOOT and FTL ($p < 0.001$; $p = 0.010$). In the transverse plane, at IC and peak during the stance phase, as expected, knee external rotation was greater in the FFOOT technique ($p < 0.001$), and the FFOOT showed greater hip internal rotation at IC and peak during the stance phase compared to 10% SR ($p = 0.013$; $p = 0.037$).

The effect size (η_G^2) between the dependent variables among the running conditions was calculated as suggested by Bakeman [1]. The most effect sizes were considered large (> 0.23).

The ANOVA test revealed a significant difference in the comfort of the running techniques ($F = 6.83$; $p = 0.002$). The USRUN (mean ± SD, 7.85 ± 2.22) showed greater subjective comfort compared to the FFOOT (6.26 ± 2.14; $p = 0.033$), 10% SR (6.75 ± 2.12; $p = 0.021$) and FTL (6.29 ± 2.12; $p = 0.002$). The pairwise comparison between techniques (FFOOT-10% SR, FOOT-FTL and 10% SR-FTL) showed no significant difference for any analysis ($p = 1.00$).

Discussion

The purpose of the current study was to assess the immediate effects of 3 running technique modifications on the lower extremity and trunk kinematics. The results of this study might help to identify running condition(s) that could improve the programs of prevention and rehabilitation of runners' injuries. A subjective assessment of comfort was performed after the execution of each technique. In partial support of our first hypothesis, only 10% SR caused reduction in peak knee abduction and peak hip adduction and FTL resulted in greater knee adduction at IC and during the stance phase. Accordingly to the second hypothesis, the FFOOT showed greater differences in knee and ankle, for the 10% SR the changes occurred at the knee and hip, and FTL caused an increase in hip and trunk angles without changing the knee angle. The USRUN was considered the most comfortable compared to the other techniques.

To the best of the author's knowledge, this was the first study to report these effects on the 3-dimensional knee and hip motions and on the ankle and trunk in the sagittal plane during different running techniques. The kinematic information in the frontal and transverse planes is especially important; as the 2-dimensional biomechanical models [15,17,34] used to calculate the PFJS in previous studies that analyzed different running techniques did not take into account these movements. For clinicians, this analysis is also relevant considering the importance of the kinematic orientations in the physiotherapy rehabilitation program. No studies had evaluated the relationship between the running technique and the comfort rating during the activity.

Our results suggest that the knee and ankle are more sensitive to the FFOOT technique. Contrary to Kulmala et al. [15] we showed a significant reduction in knee adduction at IC and an increase in knee external rotation at IC and in the stance phase that could

Table 2 Mean (SD) joint angle measure (°) for each running condition.

	Ankle	Knee			Hip			Trunk
	Plantar (−)/Dorsiflexion (+)	Flexion (+)	Adduction (−)/Abduction (+)	External rotation (−)	Flexion (+)	Adduction (−)	Internal rotation (+)	Flexion (+)
Average at initial contact								
USRUN	8.27 (6.43)	25.73 (9.04)	−2.96 (5.26)	−13.86 (6.13)	30.83 (8.63)	−8.81 (3.57)	12.80 (3.85)	7.97 (5.42)
FFOOT	−10.77 (5.79) * *,§,β	14.32 (5.86) * *,§,β	−1.42 (4.01) *,β	−20.06 (8.36) * *,§,β	32.13 (8.90)§,β	−7.63 (3.16)	13.95 (4.59)§	8.24 (6.15)β
10% SR	6.58 (7.26)α	25.56 (8.3)α	−2.45 (4.96)β	−13.16 (6.72)α,β	29.29 (8.89) *,α,β	−8.70 (3.24)	12.09 (3.87)α	8.02 (5.18)β
FTL	5.70 (6.49) *,α	25.20 (9.99)α	−3.52 (4.96) *,α,§	−14.73 (7.46)α,§	35.41 (8.92) * *,α,§	−8.43 (2.84)	12.91 (4.37)	14.16 (5.58) *,α,§
Average during the stance phase								
USRUN	11.37 (2.82)	29.89 (5.11)	−1.64 (4.54)	−9.91 (5.58)	16.10 (8.46)	−6.46 (4.08)	6.87 (5.04)	8.52 (4.92)
FFOOT	5.00 (3.85) * *,§,β	27.83 (5.38) *,β	−2.55 (4.15)§	−10.63 (5.21)	17.51 (8.67)§,β	−6.50 (2.97)	7.58 (4.06)	7.78 (5.73)β
10% SR	11.19 (2.70)α	28.51 (4.75) *,β	−1.35 (4.60)α,β	−9.72 (5.40)	15.47 (8.48)α,β	−6.48 (3.89)	6.76 (5.22)	8.40 (4.64)β
FTL	10.65 (2.87)α	30.34 (5.00)α,§	−2.53 (4.54) * *,§	−10.46 (5.56)	20.64 (8.47) * *,α,§	−6.61 (3.86)	7.01 (5.37)	14.59 (5.24) * *,α,§
Peak during the stance phase								
USRUN	23.67 (3.01)	41.46 (6.00)	3.22 (4.33)	−15.76 (6.23)	32.62 (9.05)	−10.81 (5.12)	13.06 (5.22)	9.44 (5.19)
FFOOT	19.92 (4.07) * *,β	39.05 (6.15) *,β	2.79 (3.85)	−21.30 (7.56) * *,§,β	32.76 (9.13)§,β	−10.23 (3.81)	14.65 (4.20)§	9.57 (6.16)β
10% SR	21.10 (2.98) * *,β	37.73 (5.55) * *,β	2.49 (4.37) * *	−15.20 (6.48)α,β	30.17 (9.11) * *,α,β	−9.95 (4.69) *	12.19 (5.53)α	9.19 (4.73)β
FTL	22.82 (3.25)α,§	41.93 (5.57)α,§	2.20 (4.29) * *	−16.80 (6.93)α,§	37.55 (9.40) * *,α,§	−10.67 (4.97)	13.11 (5.77)	16.01 (5.39) * *,α,§

* Significantly different from USRUN ($P<0.05$); * * Significantly different from USRUN ($P<0.001$); α Significantly different from FFOOT ($P<0.05$); § Significantly different from 10%SR ($P<0.05$); β Significantly different from FTL ($P<0.05$); USRUN, usual running; FFOOT, forefoot strike running; 10% SR, running with a 10% greater step rate; FTL, increased trunk flexion during running

have increased the dynamic knee valgus and consequently the PFJS [13,28]. On the other hand, the increased knee external rotation showed in our results could be related to the 44% knee flexion reduction at IC, as in order to flex the knee, the tibia must internally rotate in relation to the femur [9]. In the sagittal plane, the PFJS increases with greater knee flexion angles during weight-bearing tasks [27], thus our results of knee flexion reduction at IC and during the stance phase may suggest decreased PFJS during FFOOT. Recent studies reported the benefits of forefoot landing related to less PFJS [2,15]. In addition, a case series study [10] verified pain and function improvement in PFP female runners with FFOOT training. However, the increase in plantar flexion during landing requires greater triceps surae and intrinsic muscle foot activity [5]. Therefore, if the transition from the USRUN to the FFOOT is not performed gradually and associated with a strengthening program of this musculature, the practice of this technique may be accompanied with calf and/or Achilles tendon pain and injury [15].

The 10% SR resulted in greater changes in knee and hip kinematics. Our results corroborated with Heiderscheit et al. [11] as we showed peak knee flexion, hip flexion and reduced hip adduction during this technique. We also observed lower peak dorsiflexion, peak knee abduction and hip flexion angle at IC. Despite the fact that Lenhart et al. [17] had considered the peak knee flexion during the stance phase as the most important predictor of the patellofemoral joint load, we also believe that less knee abduction and hip adduction observed in our study could contribute to reduce the dynamic knee valgus [13,28]. Accordingly, in a prospective study, greater hip adduction was identified as a risk factor for female runners to develop PFP [23]. Similar to the FFOOT, the 10% SR reduced the peak knee flexion. It was hypothesized that the similarities in the knee and hip flexion angles between these 2 techniques could be related to the foot inclination angle at IC during 10% SR [11]. Our results do not confirm this hypothesis, as there was no difference in the plantar flexion angle between the USRUN and the 10% SR at the IC, beyond the significant difference between the 10% SR and FFOOT for ankle angulation at IC. In addition, the plantar pressure distribution analysis revealed that only 4 runners adopted the FFS with the 10% SR.

A 77% increase in the trunk flexion (6.19°) during FTL resulted in a significant decrease in dorsiflexion and an increase in knee adduction and hip flexion at IC and during the stance phase. The increase in knee adduction can contribute to decreasing the dynamic knee valgus [13]. In the sagittal plane, this was the only technique that increased hip flexion without causing changes in the knee flexion angle. Interestingly, a 6% decrease in the peak PFJS was found during FTL even with a small significant change in the knee flexion angle (0.9°) [17]. The slight trunk flexion resulted in an increased demand on hip extensors [29] and decreased knee extensor moment and PFJS [32]. Furthermore, it may be important to evaluate the hip and lumbar musculature before transitioning to this technique due to the higher demand on the trunk extensor musculature.

Moreover, pairwise comparisons between techniques were conducted. During the FFOOT and FTL running, the runners presented greater plantarflexion and forward trunk lean, respectively, as compared to the other running techniques. The significant differences presented in the knee frontal plane at IC and average during the stance phase showed an inconclusive result. In the transverse plane, FFOOT technique resulted in greater knee external rotation at IC and in the stance phase compared to USRUN and other conditions which could have increased the dynamic knee valgus [13,28]. While 10% SR presented positive effects in the transverse plane, such as less knee external rotation and hip internal rotation compared to FFOOT.

Considering the recreational runners, one basic requirement for the acceptance of the running modifications is associated with comfort. The USRUN was perceived as the most comfortable technique. There were no related differences in comfort perception among the 3 techniques, suggesting that there was no interference in the comfort with the kinematic changes. The potential for adherence to the 3 running techniques seems similar.

The implementation of a running technique in a runner's training program should be done gradually and ideally supervised by a knowledgeable professional with educational and strengthening exercises, considering that the running technique and the segment with greater overload might contribute to a lower risk of injury and to greater chances of success. Future studies are needed to assess the effects of training conducted for a longer period of times and in PFP runners.

Conclusion

All the evaluated running technique modifications showed different kinematic patterns that improved the lower limb alignment and could potentially reduce knee injury risk. The techniques might be considered in running training, prevention and injury rehabilitation programs.

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