12 Weeks of Simulated Barefoot Running Changes Foot-Strike Patterns in Female Runners

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- minimalist shoes
- kinematics
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- transition

Abstract

To investigate the effect of a transition program of simulated barefoot running (SBR) on running kinematics and foot-strike patterns, female recreational athletes (n = 9, age 29 ± 3 yrs) without SBR experience gradually increased running distance in Vibram FiveFingers SBR footwear over 12 weeks. Matched controls (n = 10, age 30 ± 4 yrs) continued running in standard footwear. A 3-D motion analysis of treadmill running at 12 km/h^{-1} was performed by both groups, barefoot and shod, pre- and post-intervention. Post-intervention data indicated a more-forefoot strike pattern in the SBR group compared to controls; both running barefoot ($P > 0.05$), and shod ($P < 0.001$). When assessed barefoot, there were significant kinematic differences across time in the SBR group for ankle flexion angle at toe-off ($P < 0.01$). When assessed shod, significant kinematic changes occurred across time, for ankle flexion angles at foot-strike ($P < 0.001$) and toe-off ($P < 0.01$), and for range of motion (ROM) in the absorptive phase of stance ($P < 0.01$). A knee effect was recorded in the SBR group for flexion ROM in the absorptive phase of stance ($P < 0.05$). No significant changes occurred in controls. Therefore, a 12-week transition program in SBR could assist athletes seeking a more-forefoot strike pattern and "barefoot" kinematics, regardless of preferred footwear.

Introduction

In recent years there has been a resurgence in barefoot running as well as running in light, minimalistic shoes [29]. Research into the foot-strike patterns and lower limb kinematics of barefoot and shod populations has also proliferated [4, 5, 9, 16, 17, 19, 21, 24, 34]. Habitual barefoot runners such as adolescents in Kenya's Rift Valley tend to fore-foot or mid-foot strike when barefoot, compared to habitually shod populations who tend to rear-foot strike [21]. Reduced collision forces generated with fore-foot (FFS) or mid-foot strike (MFS) patterns relative to a rear-foot strike (RFS) may account for anecdotal reports of reduced injuries in barefoot populations [28].

Runners who adopt a FFS or MFS pattern while shod also have reported improved performances [16, 17] and reduced injuries [8, 10, 13], spurring industry and researchers to examine foot strike patterns (FSP) more closely and to question the design of standard modern cushioned running shoes, which encourage RFS. Vibram FiveFingers is a footwear brand aimed at simulating barefoot running (SBR). A thin flexible rubber sole protects the sole of the foot from the environment, while still allowing flexibility and proprioception [35]. Running kinematics and ground reaction forces during SBR are reportedly similar to the barefoot condition of habitual barefoot runners [34].

There are several studies of kinematic and FSP differences between barefoot and various shod conditions but findings vary according to the population under investigation. At velocities typical of endurance running (3.33–4.5 m/s^{-1}), habitually shod runners tend to land with a dorsiflexed ankle and RFS pattern, both when running shod and (to a lesser degree) when barefoot [3, 4, 9, 21]. In contrast, at similar velocities, habitual barefoot runners reported FFS or MFS patterns, with a more plantarflexed ankle at foot strike, than habitually shod populations, both when assessed barefoot and shod [24, 28]. Therefore, motor patterns laid down over years of training will influence FSP and running kinematics more than the shoe, or lack thereof, worn on a specific testing occasion. If a FFS/MFS pattern is

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sought by an athlete, simply changing footwear may not be sufficient to alter these patterns.

Despite this, most studies have evaluated the acute effects of shod and barefoot running on kinematics, kinetics, spatiotemporal variables or oxygen cost of running, with minimal or no opportunity beforehand for the participant to habituate to any alternative footwear condition [4,5,9,11,14]. This is understandable, as the amount of time required to habituate to another footwear condition is not established, and transition to barefoot, SBR or FFS running could, by itself, involve risk of injury [13,26,31].

It has been reported that habitually barefoot athletes run differently from shod athletes [4,9,21,34]. However, it remains unclear as to whether adults who have grown up running in shoes will run with "barefoot" kinematics following a habituation period, or how long that habituation period should be. Previous studies attempting to influence running motor patterns or kinematics through plyometric, strength or neuromuscular interventions have typically been 6–9 weeks in duration [3,10,23,33,38]. A 12-week program was chosen for this study to allow initial adaptation of musculoskeletal structures to new forces, with the purpose of reducing the risk from too rapid a transition [13,26,31]. Thereafter higher SBR training loads could be gradually introduced to elicit a training effect. Thus, the current study investigated whether a 12 week transition program of SBR would alter FSPs and stance-phase kinematics at the knee and ankle in habitually shod adult female recreational runners. It was hypothesized that (1) post-intervention barefoot kinematics would be different to pre-intervention following SBR training; and (2) that some carry-over of "barefoot" type kinematics might transition into shod gait, post-intervention, in the SBR group.

Methods

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Participants

An a priori power analysis was conducted for expected outcomes with a type I error probability of 0.05 and a power of 0.8. This analysis indicated that n = 10 would provide a statistical power of ~80% (G*Power v3.0.10 free software; Institute of Experimental Psychology, Heinrich Heine University, Dusseldorf, Germany). In order to utilize a control group, and to allow for attrition from the study, 30 female recreational runners ages 18–35 yrs were recruited from collegiate and local clubs as well as via university notice boards. All participants were running in standard cushioned shoes prior to study enrolment, which included neutral, stability, and anti-pronation type models. All were running > 15 km per week for at least the previous 6 weeks, with the intention of continuing at a similar intensity for the following 12 weeks. In addition, all had prior experience of treadmill running. Participants were excluded if they had any neurological or musculoskeletal condition that had prevented them from training in the previous 6 months; were currently attending physiotherapy or following a lower limb rehabilitation or prehabilitation program; were currently or had ever ran in minimalist or SBR footwear; or ran in "racing flats" in training (usage in races was allowed). The pre-participation questionnaire collected information on each participant's age, average weekly running distance, and the type and number or other sports/forms of exercise undertaken weekly. Using this stratified data, participants were assigned to an intervention group (SBR, n = 15; mean (SD) age 30 (4) yrs, height 1.64 (0.07) m, BMI 21.6 (1.5) kg/m^{-2}, weekly running distance 30.9 (15.3) km), or a control group (n = 15, mean (SD) age 29 (3) yrs, height 1.66 (0.05) m, BMI 21.6 (2.5) kg/m^{-2}, weekly running distance 29.1 (11.8) km) with similar age and activity level profiles. The study was conducted in accordance with international ethical standards [15], and ethical approval was granted by the Faculty of Health Sciences Ethics Committee of Trinity College, Dublin. Prior written consent was obtained from all participants.

Experimental protocol

SBR and Control groups were assessed pre- and post-intervention running at 3.33 m/s^{-1} (12 km/h^{-1}) on a conventional motorised treadmill (Proform 700 ZLT, Utah, USA) in both barefoot and shod conditions. This velocity was chosen in order to be representative of a comfortable running pace for a recreational running population, and to allow comparison with the findings of other authors who previously assessed barefoot and shod running kinematics at similar velocities of 3.0–3.5 km/h^{-1} [9,24,34]. Participants ran shod first on both testing occasions. This order was chosen as shod running was the standard training condition for all participants at baseline. Moreover, we wanted to discount the possibility of a task performed immediately prior (barefoot running) having caused motor pattern carry-over as a source of type 1 error, should the hypothesis for changes to shod kinematics be accepted [18]. Test conditions were identical on both occasions and took place indoors in a temperature-controlled room with artificial lighting. Participants avoided strenuous exercise in the 24 h pre-test and warmed-up according to their usual routines. All participants wore standard, neutral cushioned shoes (Adidas Duramo, weight 250 g, EVA/Adiprene sole) for the shod trials. Following placement of kinematic markers in each condition, participants ran at a self-selected velocity for at least 4 min to become comfortable running on a treadmill with gait analysis equipment attached [11]. After 4 min, treadmill velocity was increased to 3.33 m/s^{-1} for > 50-s before a data collection epoch (duration 5-s). All participants expressed comfort with treadmill running with kinematic markers attached before data acquisition and were not aware of when kinematic data was being captured. A 10-min break followed the shod trial, during which participants performed active recovery, and kinematic markers were changed from running shoes to the bare feet. Participants received no verbal instruction or encouragement on how they should run in either condition and were not informed of what kinematic variables were being assessed or of the study hypotheses.

Intervention

Each participant in the SBR group was given an appropriately fitted pair of Vibram FiveFingers Classic model shoes (3.5 mm rubber sole, 120.5 g for women's size 37). Foot strengthening exercises were prescribed for weeks 1 and 2 of the 12-week program according to the manufacturer's recommendations [37]. The remainder of the transition program for the SBR group was devised by the lead investigator and sent to participants by e-mail at weeks 1, 5 and 9. In week 1, participants only walked indoors in the minimalist footwear. In week 2, the SBR load was increased to {walk × 5 min + jog × 1 min} by 3 repetitions on 3 occasions. From weeks 3–8, participants ran 3 times per week, with at least 1 day in between each SBR session. Starting with 3 × 5 min runs/week in week 3, and increasing run times by 5 min/SBR session each week, the SBR load gradually increased so that by week 8 a participant would be performing SBR a maximum of 3 × 30 min sessions per week. For weeks 9–12, participants were contacted individually and an SBR running plan was devised to meet their individual needs. Training sessions were not supervised, nor was there any orientation session on SBR running. Participants were free to develop their own running pattern during SBR training. However, for participant safety reasons, SBR participants were advised at the start of the transition program that over-striding or adopting an RFS pattern in the SBR footwear may increase the likelihood of pain or injury and were thus best avoided. Stretching calf muscles and self-massage of the calf and foot, before and after each run, were also encouraged. Time off from training to allow for holidays/work commitments or rest from muscle soreness was permitted, and participants were advised not to progress to the following week's program until they had comfortably completed 3 SBR runs of the recommended duration. Satisfactory completion of the protocol was set at having completed at least 9 of 12 weeks of the program, and to have performed SBR training for at least 30 min on 3 occasions per week during the final 2 weeks of the program. Throughout the program SBR participants could complete additional training in their regular running shoes to maintain individual training volumes. Controls continued training in their own standard running shoes throughout the intervention time period, and were not permitted to run in shoes other than cushioned neutral, stability or anti-pronation models. Training logs and injury data were collected by e-mail from both groups every 2 weeks.

Equipment and data collection

3-dimensional running kinematics was captured and analysed using the Coda Dual CX1 system (Charnwood Dynamics, Rothley, UK). 2 sensor units placed equidistant (3 m) and orthogonally to the left and right sides of the sagittal plane of the participant captured horizontal and vertical motion of active infrared LED markers attached to discrete anatomical locations on the participant. Signals were cross-correlated in real time, and 3-dimensional marker trajectories were sampled at 200 Hz. 20 markers (10 per side) were located as follows: on the pelvic frame (ASIS and PSIS), femoral wand (anterior and posterior), knee joint centre (lateral joint line, 15 mm anterior to the level of the head of the fibula), tibial wand (anterior and posterior), lateral malleolus, lateral calcaneus (heel) and overlying the 5th metatarsal head (▶ **Fig. 1**). Skin adhesive spray and tape were used to minimise artefact marker movement on the participants' skin. For shod trials, kinematic markers were placed on the shoe upper, overlying the foot landmarks. Before each testing procedure, anthropometric variables of height, mass, pelvic width, pelvic depth, knee joint width and ankle joint width were assessed. Reference points were calculated by software for the sacrum, hip, knee and ankle joint centres and for thigh, shank and foot segments. Eulerian joint angles and segment rotations were calculated automatically for every time point by Codamotion segmental analysis (Version 6.76.4). Standing calibration trials were recorded for all participants before each running trial in order to assess test-retest reliability of marker placement. As noted by previous researchers [38], variations in posture during the standing calibration trials can affect the calculation of static joint angles. Therefore, the separation (in mm) between knee and ankle markers at each testing occasion was used to assess reliability of marker position. Interclass correlation coefficients (ICC) and absolute technical error of the measurement (TEM) were calculated for pre- and post-data in both the barefoot and shod conditions. ICC data were 0.92 and 0.93, while absolute TEM data were 6.0 and 5.6 mm for barefoot and shod, respectively.

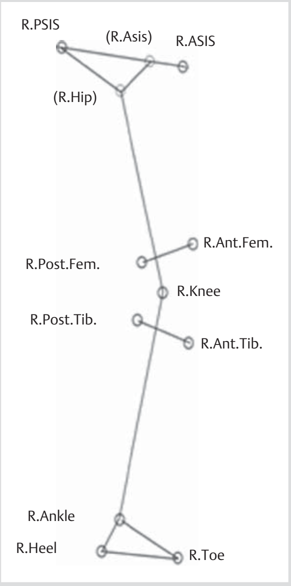

Fig. 1 Schema of marker position for segment calculation with CODA. Hip joint centre (R.Hip), and (R.Asis) are virtual markers calculated from PSIS and ASIS marker positions and participant pelvic measurements. R.Post.Fem, R.Ant. Fem and R.Post. Tib, R.Ant.Tib are located on the femoral and tibial wands, respectively, and secured to patient's skin. Adapted from Coda CX1 user guide, (Charnwood Dynamics Limited, 2008, pp. 62.).

As with most studies of running kinematics [4,9,21,34] the stance phase of gait (time between foot-strike and toe-off) was examined in this study. Because an instrumented treadmill was not available, the stance phase was identified kinematically. Toe-off was identified by using peak knee extension [12]. Foot-strike was identified for a RFS using the 2nd peak in vertical acceleration of the heel marker [20]. The 2nd peak of vertical acceleration of the toe marker (5th metatarsal head) was used to identify FFS, as this is the part of the foot which contacts the ground first during FFS [21,24]. An initial pilot study identified this protocol to be satisfactory. The treadmill trials were conducted at a moderate pace (3.33 m/s^{-1}) and all participants ran with a heel-down then toe-down or toe-down then heel-down pattern, rather than a sprinting style up-on-toes gait [8,16]. Therefore, marked RFS patterns had a long latency between heel and toe peaks, and vice versa for marked FFS patterns. The FSPs observed visually and/or via Coda real-time views that displayed a flat or mid-foot strike had a very small latency between peaks (< 5 ms), as heel and toe markers made contact almost simultaneously when the lateral border of the foot contacted the ground [16,21]. For each trial, 5 s of data were collected from the participant's left leg. Data were filtered using the Coda software.

Data reduction

5 stance phases were extracted from each 5-s data epoch and transferred to Matlab for processing using customised programmes (Matlab, V7.14 R2012a, Mathworks, MA, USA). Temporal information (in ms) for heel-toe latency (positive for RFS, negative for FFS) and ground contact time (GCT) were initially calculated. Strides were then temporally normalised to 100 data points using cubic spline fitting in order to eliminate inter-stride variations in duration. Discrete kinematic variables were subsequently identified. Variables included ankle and knee flexion angles at foot strike and at toe-off, peak knee flexion, peak ankle dorsiflexion, and knee and ankle ROM in the absorptive phase of stance (maximum flexion minus flexion angle at foot strike).

Statistical analysis

Data from participants who completed both pre- and post-testing in each group (SBR, n=9; Control, n=10) were combined to form a group mean and SEM for kinematic and spatiotemporal variables. A repeated measures design was used with results compared within groups across time (pre- vs. post-intervention) and between groups (SBR vs. Control) pre- and post-intervention. Data within shod and barefoot running trials were analysed separately. Normality of data was assessed using the D'Agostino and Pearson omnibus normality test. Where all data across time and group for a variable were normally distributed, a 2 way ANOVA with time as a repeated measure was used to analyse the data. Where a significant interaction or main effect was detected on ANOVA, differences across group or time were quantified using Sidak's post-hoc multiple comparison test, where $P<0.05$ inferred significance. For variables where data were not normally distributed, Wilcoxan and Mann Whitney U tests were utilised, with Bonferroni corrections for multiple comparisons. All statistical tests and analyses were performed using GraphPad Prism version 6.00 (GraphPad Software, CA, USA).

Results

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Of the 15 participants randomised into each group, 9 SBR and 10 control participants completed the study protocol and were included in the final analysis. Drop-outs from the study did not have repeat analysis of running kinematics at exit. This was unavoidable in those participants (8 of 11) who dropped out due to injury. However, group baseline characteristics remained similar despite drop-outs (◉ **Table 1**). In the Control group, one participant commenced a neuromuscular/strength training programme, and 4 incurred injuries requiring physiotherapy/rehabilitation of >3 weeks duration (lumbar back pain/sciatica, anterior knee pain, ITB syndrome, back pain). In the SBR group, one participant reported minimalist footwear to be uncomfortable and dropped out after week 2. Another did not complete the program due to university examinations. One sustained a traumatic calcaneal fracture not related to running and another reported hip and calf pain in weeks 9–12. One SBR participant experienced pain in the 2nd metatarsal during week 8, was advised to stop the program, but continued shod sports without pain. Another sustained a metatarsal stress fracture in week 7, was diagnosed as osteoporotic (T-score −2.7) and was referred to specialist care.

Temporal and kinematic data for both conditions are presented in ◉ **Table 2**. FSP (heel-toe latency) and joint ROM plots for the ankle and knee during stance phase are presented in ◉ **Fig. 2, 3**, respectively.

Barefoot trials

A significant main effect for time was noted for ankle flexion angle at toe-off {F(1,17)=13.79, P=0.002}. Post-hoc analyses revealed a significantly more plantarflexed ankle at toe-off post-intervention compared to pre-intervention in the SBR group ($P<0.01$), with no significant change recorded in the control group across time (◉ **Table 2**). Heel-toe latency (FSP) data in the control group pre-intervention was non-normally distributed. Therefore, differences across group and time were analysed

Table 1 Participant characteristics. Mean with SD in parentheses.

	Control group (n=10)	SBR group (n=9)
age (yrs)	30 (4)	29 (3)
mass (kg)	56.6 (4.2)	60.9 (10.5)
height (m)	1.63 (0.06)	1.66 (0.06)
BMI (kg/m^{-2})	21.2 (0.7)	22.1 (2.5)
distance/week (km)	30.4 (17.5)	28.9 (11.5)

Table 2 Mean ± SEM data for ground contact time (GCT), heel-toe latency and kinematic variables for SBR and Control groups. For heel-toe latency, positive data infer rear-foot strike (RFS) and negative data infer fore-foot strike (FFS). For ankle flexion at foot-strike and toe-off, negative data infer plantarflexion and positive data infer dorsiflexion. A straight (fully extended) knee would be 0°. Asterisk (*) denotes SBR group post-intervention significantly different to pre-intervention. Plus (+) denotes Control group post-intervention is significantly different from SBR group post-intervention. (* or + infers $P<0.05$, ** or ++ infers $P<0.01$ and *** or +++ infers $P<0.001$).

Variable	Running condition	Pre-intervention		Post-intervention	
		Control (n=10)	SBR (n=9)	Control (n=10)	SBR (n=9)
GCT (ms)	*barefoot*	221 (7)	232 (8)	219 (10)	230 (7)
	shod	238 (7)	251 (8)	237 (9)	243 (8)
heel-toe latency (ms)	*barefoot*	2.8 (3.8)	−7.4 (4.5)	2.4 (3.6)+	−14.3 (2.9)
	shod	20.8 (1.7)	21.8 (1.8)	21.3 (1.6)+++	−3.6 (7.7) ***
ankle flexion angle at foot-strike (°)	*barefoot*	−4.2 (2.0)	−5.5 (2.5)	−4.2 (1.7)	−7.1 (2.1)
	shod	0.4 (1.1)	0.2 (1.4)	−0.6 (1.1)++	−8.4 (2.4) ***
peak ankle dorsiflexion in stance (°)	*barefoot*	20.0 (1.6)	22.0 (1.8)	18.5 (1.0)	20.9 (1.8)
	shod	21.4 (1.0)	22.5 (1.2)	19.7 (0.9)	19.3 (1.1)
ankle ROM in absorptive phase (°)	*barefoot*	24.2 (1.3)	27.5 (2.3)	22.7 (1.6)	28.0 (2.4)
	shod	20.9 (1.0)	22.3 (0.7)	20.3 (1.0)+++	27.7 (1.9) **
ankle flexion angle at toe-off (°)	*barefoot*	−26.8 (3.5)	−34.3 (2.3)	−28.2 (3.8)	−38.3 (2.0) **
	shod	−21.3 (2.8)	−27.1 (2.0)	−23.1 (3.0)+	−33.2 (1.9)**
knee flexion angle at foot-strike (°)	*barefoot*	17.3 (1.3)	19.8 (1.0)	17.7 (1.0)	19.8 (1.4)
	shod	15.7 (1.4)	16.1 (1.5)	14.8 (0.7)	15.9 (1.3)
peak knee flexion angle during stance (°)	*barefoot*	40.9 (1.5)	42.2 (1.8)	40.1 (1.1)	40.2 (1.9)
	shod	44.5 (1.6)	46.7 (1.8)	43.1 (1.3)	43.7 (1.5)
knee flexion ROM in absorptive phase (°)	*barefoot*	23.6 (0.6)	22.4 (1.4)	22.4 (1.3)	20.4 (1.3)
	shod	28.8 (0.6)	30.6 (1.5)	28.3 (1.0)	27.7 (1.8) *
knee flexion angle at toe-off (°)	*barefoot*	14.3 (2.1)	11.6 (2.3)	13.8 (2.2)	10.0 (1.8)
	shod	13.9 (2.5)	12.0 (2.4)	13.7 (1.9)	9.8 (1.5)

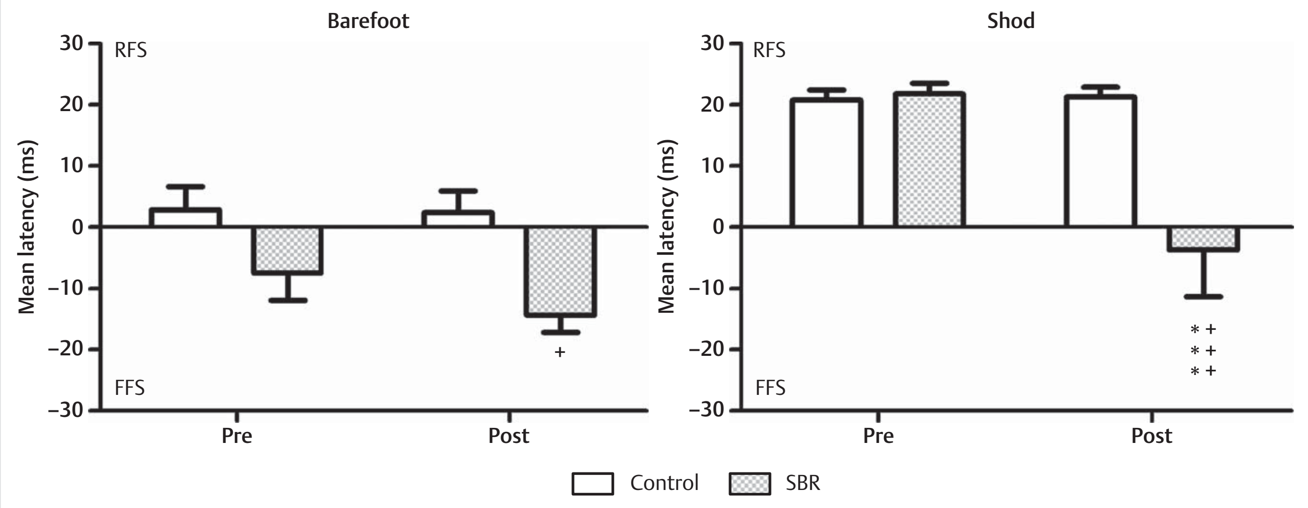

Fig. 2 Mean ± SEM heel-toe latency at foot-strike. Negative data infer fore-foot strike (FFS) and positive infer rear-foot strike (RFS). Asterisk (*) denotes significant differences comparing pre- and post-intervention data within group. Plus (+) denotes significant differences between SBR and Control group post-intervention. (++ infers $P<0.01$, *** or +++ infers $P<0.001$).

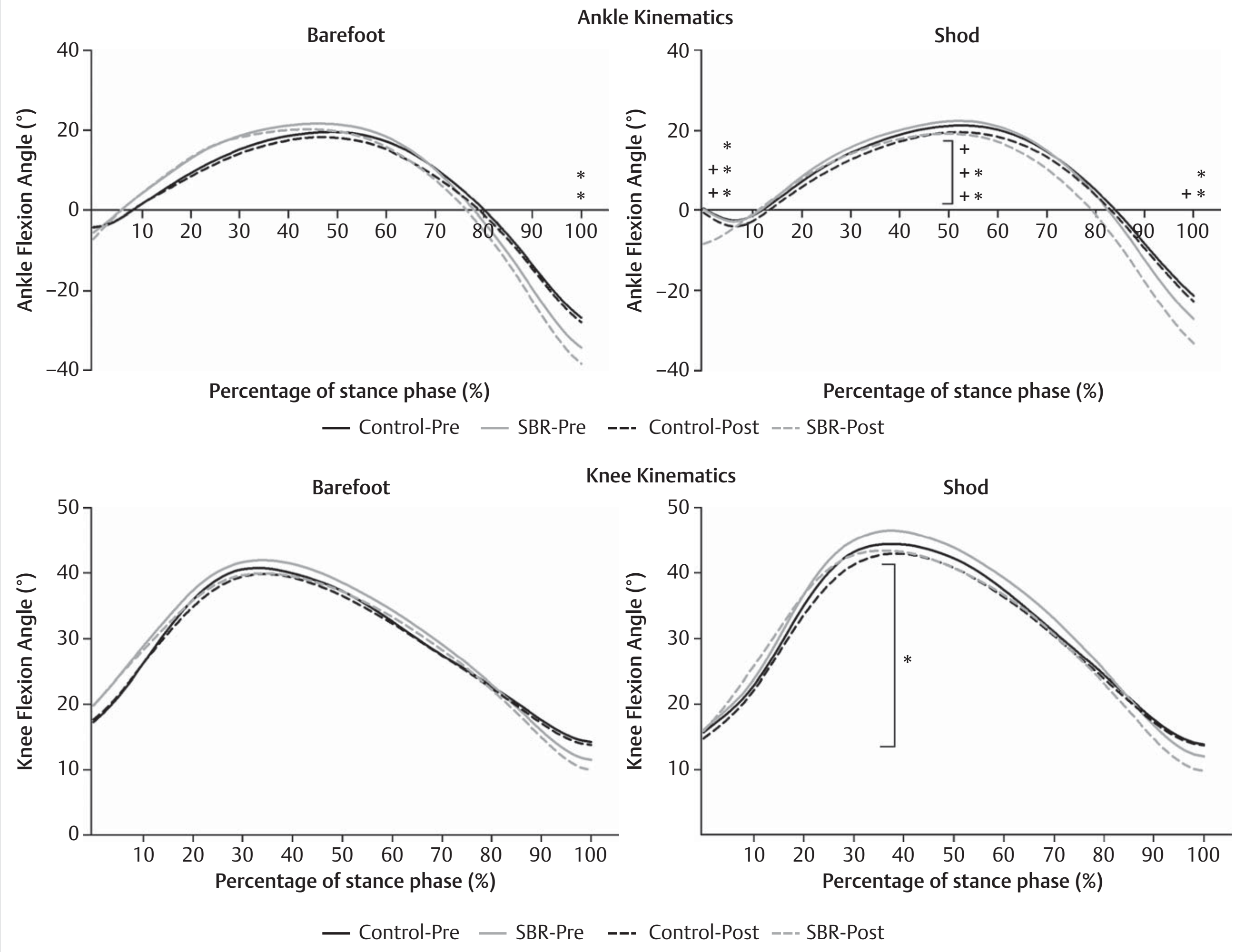

Fig. 3 Group mean ankle and knee flexion kinematic graphs during stance phase of the gait cycle. Negative data indicate plantarflexion. Asterisk (*) denotes SBR post-intervention significantly different from pre-intervention. Plus (+) denotes SBR post-intervention significantly different from Control post-intervention. Square bracket indicates joint flexion ROM between foot-strike and peak joint flexion. (* or + infers $P<0.05$, ** or ++ infers $P<0.01$ and *** or +++ infers $P<0.001$).

using non-parametric tests. A significant difference in FSP was observed between SBR and Control groups post-intervention (Mann Whitney U test with Bonferroni correction, $P<0.05$), with no significant difference between groups pre-intervention or within groups across time (▶ **Table 2** and ▶ **Fig. 2**).

Shod trials

When assessed running shod, a significant group-by-time interaction was observed for heel-toe latency $\{F(1,17)=13.52, P=0.002\}$. Post-hoc analyses revealed a significant change in FSP across time from RFS to FFS in the SBR group ($P<0.001$), with no significant change in controls. A significant difference in FSP between groups was also observed post-intervention ($P<0.001$), with no significant difference between groups pre-intervention (▶ **Table 2** and ▶ **Fig. 2**). For kinematics at the ankle, significant group-by-time interactions were observed for ankle flexion angle at foot strike $\{F(1,17)=10.68, P=0.005\}$ and for ankle flexion ROM in the absorptive phase of stance $\{F(1,17)=8.367, P=0.01\}$. Significant main effects were also observed across both time $\{F(1,17)=9.454, P=0.007\}$ and group $\{F(1,17)=5.715, P=0.029\}$ for ankle flexion angle at toe-off. Post-hoc analyses revealed the following: a significantly more plantarflexed ankle in the SBR group at foot-strike and at toe-off post-intervention when compared with their own pre-intervention data ($P<0.001$, $P<0.01$) and compared with controls post-intervention ($P<0.01$, $P<0.05$); a greater ankle ROM in the absorptive phase of stance in the SBR group post-intervention, both compared with pre-intervention ($P<0.01$) and compared to controls post-intervention ($P<0.001$). At the knee, a significant main effect for time was observed for flexion ROM in the absorptive phase of stance $\{F(1,17)=4.475, P=0.05\}$, with post-hoc analysis revealing a significant decrease in knee ROM across time in SBR ($P<0.05$). No significant differences were recorded between groups pre-intervention for any of the kinematic variables measured, and no significant changes were recorded across time in the Control group (▶ **Table 2** and ▶ **Fig. 3**).

Discussion

This is the first study to have investigated the effect of SBR training on barefoot and shod kinematics. The results of the current study highlight that a 12-week intervention of controlled SBR training was sufficient to elicit significant changes in lower limb kinematics which are manifest not only during barefoot running, but also during running in regular cushioned running shoes.

Barefoot kinematics

Differences between barefoot and shod kinematics observed in this study were similar to those observed by others, namely: shorter ground contact time [4, 9, 34], a more MFS or FFS pattern [21, 34], a more plantarflexed ankle at foot-strike [4, 9, 21, 34] and at toe-off [4], a greater ankle ROM during the absorptive phase of stance [34], greater knee flexion at foot-strike [9], and lower peak knee flexion [4, 9, 21, 24] and ROM [24]. The hypothesis that further changes would occur in barefoot kinematics after 12 weeks of SBR was supported by significantly greater ankle plantar flexion at toe-off vs. pre-intervention. In the current study, 100% of the SBR group adopted a non-RFS pattern and plantarflexed ankle at foot-strike when running barefoot post-intervention. These data are similar to habitual barefoot runners whose group mean indicated MFS [34], barefoot adolescent Kenyans (78% non-RFS) [21] and habitually barefoot American adults (75% non-RFS) [21]. The post-intervention barefoot kinematics of the SBR group differs from other authors' reports of barefoot kinematics in habitually shod runners. These studies showed a RFS [9, 21] and dorsiflexed ankle angle at foot-strike [4, 5, 9, 21], even in the barefoot condition. This supports the notion above that reports of "barefoot kinematics" must be interpreted with caution and that consideration be given to the amount of previous barefoot or SBR experiences of the cohort.

Shod kinematics

All participants (n=30) ran with a RFS pattern when shod pre-intervention. This agrees with the findings of other authors [9, 17, 19, 21], who reported 88.9–100% of habitually shod recreational runners to exhibit a RFS pattern. The significant changes across time in the SBR group for FSP and kinematics at the ankle (ankle flexion at foot-strike, toe-off and ankle ROM) and knee (reduced flexion ROM) supported the carry-over hypothesis from SBR to shod gait. In the SBR group, 56% of participants (5 of 9) were running with a non-RFS pattern post-intervention when shod, with a mean ankle flexion angle at foot-strike indicating plantar-flexion. This is similar to reports of non-RFS patterns during shod gait in 50% of habitually barefoot US adults and 71% of recently-shod Kenyans from similar sample sizes [21]. Differences in methodology make comparisons of absolute data for ankle and knee flexion angles between studies difficult. However, the direction of significant changes in shod kinematics in the SBR group across time was towards that observed during barefoot gait in the same participants and towards the kinematics of habitually barefoot or SBR participants in other studies [21, 34].

Physiological background for changes observed

We hypothesize that neuromuscular adaptations through the SBR training program are responsible for the marked change in shod kinematics post-intervention. This is despite SBR participants continuing to complete some of their training in regular running shoes. During the final weeks of the study, SBR comprised the majority of all intervention group participants' running training. We speculate that the altered FSP induced by SBR training over 12 weeks, repeated over many gait cycles, would have produced motor learning and training effects, both on muscle recruitment patterns of motor units at the knee and ankle [3, 30] and on pattern generators in the CNS [32]. Research has suggested that plantar surface and heel sensation induces a protective response whereby runners alter behaviours to reduce landing shocks, and that cushioned shoes provoke reduced shock modifying behaviours [9, 21, 28]. In barefoot or SBR, the lower limb segments align their "touchdown geometry" to avoid a heavy RFS pattern [9, 24]. Cyclical movement patterns such as running lead to the creation of specific neural connections within the reticulospinal neurons and central pattern generators by repetitive actions [32]. Researchers have pointed out that, in normal situations, joint movements are primarily determined by the "preferred movement path" in each joint [22, 34]. This is supported by the similarity within populations in running kinematics across footwear conditions where there has been no transition or habituation period [4, 9, 21, 34].

The current results suggest that changes in running motor patterns of adult females who have spent a lifetime running shod can be induced in 12 weeks and, moreover, that these motor pattern changes developed by SBR will pervade across footwear conditions. The success of such a relatively short intervention in altering motor patterns may be compared to the significant improvements in running performance or economy observed in plyometric and resistance training interventions in runners [3, 23]. Most of these studies involved training interventions 2–3 times per week, with significant differences relative to controls being observed after 6–10 weeks. It is a well-established principle in resistance training that initial gains in strength are a result of neuromuscular adaptations [30]. We can assume that such neuromuscular adaptations had occurred by the conclusion of our study and also that strength and eccentric endurance gains were likely in the triceps surae, allowing participants to maintain the new FSP for the duration of a typical training session (~30 min for weeks 10–12). These parameters were not measured but may be the subject of future research. The significantly increased ankle plantarflexion at toe-off, post-intervention in the SBR group both barefoot and shod cannot be attributed directly to segment alignment at foot-strike. One could postulate that neuromuscular coordination or strength improvements in the triceps surae induced by SBR training may have played a role. It could also be due to altered mass-spring mechanics [2], whereby elastic storage and recovery in the Achilles tendon and plantar fascia [1] are more effectively harnessed as participants stretch these structures to a greater degree during FFS. Because the gastrocnemius musculature originates on the distal femur, the Achilles tendon-triceps surae complex (ATTSC) is slackened as the knee bends [24]. The smaller knee flexion ROM in the absorptive phase of stance post-intervention barefoot ($P = 0.18$) and shod ($P < 0.05$) in the SBR group would reduce this "slackening." This could account for greater force development in the ATTSC and increased ankle flexion at toe-off as a result. This could potentially result in improvements to performance and to running economy [24].

Safety and acceptability of SBR as an intervention

Injury and non-adherence rates were similar for both groups. Hence, a 12 week time-frame and programme could be recommended for runners wishing to safely transition to SBR or incorporate SBR as a training technique. The 7 injuries directly attributable to running (20 and 26%, in SBR and Control groups, respectively) reflect the high incidence of running injuries reported in the literature [36] and suggest that there may not be an excess risk from a controlled transition to SBR. However, it is acknowledged that the sample size restricts interpretation of injury data. The metatarsal stress injuries recorded in 2 SBR participants emphasises the increased risk in female runners for such injuries and supports previous recommendations for a slow transition [26]. We suggest that female runners at risk for low bone mineral density exercise extreme caution when taking up SBR or barefoot running, and consider DEXA to rule out osteopenia or osteoporosis.

Limitations and directions for future research

We acknowledge limitations of the study methods. A larger sample size could have increased the statistical power such that more variables achieved significance, especially given that some exhibited consistent trends in kinematics but were not statistically significant. Participants were aware of group assignment at the initial testing session (but not of the study hypothesis). Due to the nature of the study, participant blinding to the intervention being received was impossible. The lead investigator collected training data during the course of the study (in addition to all kinematic data) and was therefore not blinded to participant group allocation at the time of testing. As all measures were objective this should not have led to bias. Treadmill gait and over-ground gait are not identical [20, 27]. However, treadmill usage allowed participants to adapt to each condition and reach a steady state in their stride pattern before data sampling occurred. Not knowing when data would be acquired also had other potential benefits when compared with over-ground testing and use of force-plates [4, 24]. For the transition program, SBR sessions were prescribed based on time rather than distance or intensity to simplify the protocol and encourage compliance. This, however, makes it more difficult to quantify the "dose" of the intervention received by each participant or the amount of SBR training as a proportion of total training volume for each individual. While future research may seek to standardise the transition protocol, this should be done cautiously since individuals progress differently, and higher injury rates may ensue from enforcing progression. The current study was delimited to recreational female athletes. Therefore, one should be wary of extrapolating the results to highly trained athletes, whose running mechanics may be highly consistent [4, 6]. Care should also be taken when comparing kinematic data from this study with that of studies in which participants were tested running at higher velocities [4, 5, 21]. Running kinematics and ankle proprioception in the footwear used in this study have been shown to be similar to barefoot [34, 35]. However, no shoe exactly replicates barefoot running and one should not make this assumption when discussing SBR.

Conclusion

The findings of this study indicate that changes in motor patterns in previously habitually shod runners are possible and can be accomplished within 12 weeks. There is emerging evidence that a FFS pattern such as developed over time by SBR could have performance benefits [16, 17, 24] and perhaps lead to lower injury rates [8, 13] or the potential to treat existing injuries [7, 10]. The more FFS pattern observed in shod gait by the SBR group post-intervention led to significantly lower knee flexion ROM in the absorptive phase of stance and may reduce stress across the patellofemoral joint [4, 5, 25]. The simplicity and relatively low cost of the intervention makes it accessible to both recreational and competitive athletes who may wish to develop a more "barefoot-like" running pattern, regardless of preferred footwear condition.

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