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Six Weeks Habituation of Simulated Barefoot Running Induces Neuromuscular Adaptations and Changes in Foot Strike Patterns in Female Runners

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Background: The aim of this study was to examine the effects of a 6-week training program of simulated barefoot running (SBR) on running kinetics in habitually shod (wearing shoes) female recreational runners.

Material/Methods: Twelve female runners age 25.7±3.4 years gradually increased running distance in Vibram FiveFingers minimal shoes over a 6-week period. The kinetic analysis of treadmill running at 10 Km/h was performed pre- and post-intervention in shod running, non-habituated SBR, and habituated SBR conditions. Spatiotemporal parameters, ground reaction force components, and electromyography (EMG) were measured in all conditions.

Results: Post-intervention data indicated a significant decrease across time in the habituation SBR for EMG activity of the tibialis anterior (TA) in the pre-activation and absorptive phase of running ($P<0.001$). A significant increase was denoted in the pre-activation amplitude of the gastrocnemius (GAS) between the shod running, unhabituated SBR, and habituated SBR. Six weeks of SBR was associated with a significant decrease in the loading rates and impact forces. Additionally, SBR significantly decrease the stride length, step duration, and flight time, and stride frequency was significantly higher compared to shod running.

Conclusions: The findings of this study indicate that changes in motor patterns in previously habitually shod runners are possible and can be accomplished within 6 weeks. Non-habituation SBR did not show a significant neuromuscular adaptation in the EMG activity of TA and GAS as manifested after 6 weeks of habituated SBR.

MeSH Keywords: **Electromyography • Female • Running**

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Background

According to the authors of a 2004 article published in Nature, humans were born to run [1]. Bramble and Lieberman have suggested that our body structure was significantly influenced by the fact that we needed to run for survival [1]. A growing contingency believes that we were designed with all we need in our feet to be able to run without shoes or with minimal shoes that mimic the barefoot running striking pattern. In fact, there has been a suggestion that running without the assistance of modern running shoes might lead to a reduction in the incidence of running injuries [2].

Barefoot running has been resurgent in recent years as well as running in minimalistic shoes [3]. Research into different patterns of foot-strike and the kinematics of lower limb of barefoot and shod running has similarly proliferated [2,4–6]. Habitual barefoot runners run with a fore-foot strike (FFS) or mid-foot strike (MFS), compared to habitually shod runners who tend to run with a rear-foot strike (RFS) [2]. Decreased collision forces created with FFS or MFS patterns in relation to RFS might justify the anecdotal reports of decreased injuries in barefoot runners [7].

Kinematics and kinetics analysis of simulating barefoot running (SBR) are apparently analogous to the barefoot condition of habitual barefoot runners [6,8]. Findings from several studies of kinematic and kinetics differences between barefoot and shod running vary according to the population under investigation. At typical velocities of endurance running (3.33–4.5 m/s^{-1}), habitually shod runners tend to land with a dorsiflexed ankle and heel-strike pattern [9,10].

On the contrary, at similar velocities, habitual barefoot runners tend to run with a FFS or MFS patterns, landing with a more plantarflexed ankle at initial contact than do habitually shod runners [5]. Therefore, training will induce motor changes influencing the foot-strike patterns (FSP) and the kinematics of running. However, most studies have evaluated the acute changes in kinematics, kinetics, spatiotemporal variables, or oxygen cost during shod and barefoot running without an opportunity to habituate to the barefoot running [10–12]. This is understandable, as the required amount of time for a safe transition into barefoot running is not established yet, and the transition to simulated barefoot running, by itself, might involve higher risk of injury [13,14].

Neuromuscular control during running is influenced by landing pattern and type of shoes worn [15,16]. In RFS running pattern, the TA muscle is considered to be the muscle of specific interest. The TA muscle has 2 major functions during initial contact: it dorsiflexes the ankle before heel-strike, and it decrease the plantar-flexion moment created around the ankle joint due to the heel-strike [17,18]. The purposes of these 2 functions are somewhat different. The positioning of the foot requires a concentric contraction of the TA to assume the dorsiflexed position during heel-strike, whereas the reduction of the foot-slapping movement is associated with eccentric contraction of the TA to control the plantar flexion moment created during heel-strike. Consequently, we can postulate that the activity of the TA muscle should be considerably different in the pre- and post-heel-strike phase and should be changed while running with an FFS versus RFS [15,19].

Ground reaction force (GRF) is an important factor in the study of the kinetics of the lower extremities during running. The muscular activity of the lower limb is altered in response to ground reaction forces. During running, the human body reacts to input from its external environment. One such input is the GRF, which occurs during the ground contact phase of each stride [16]. One possible reaction is the modification of the muscle activity patterns in response to that force [20]. It has been speculated that there is a requirement for the muscles to control and, thus, minimize soft-tissue vibrations during locomotion [20] and, thus, that there will be a change in muscle activity patterns in response to different vibration loadings on the lower extremity.

Impact forces in heel-toe running are forces resulting from the collision of the heel with the ground, reaching their maximum (the impact peak) earlier than 50 ms after first contact [20]. The rate at which the impact peak is reached is termed the loading rate and is a correlate of the major frequency of the impact peak. Impact forces have frequency contents of 10–20 Hz and should be expected to produce vibrations of the soft tissues of the body. Changes in the myoelectric patterns of the lower extremities of the muscle activities have been shown to respond to frequencies of applied continuous vibrations of different impact forces.

A major limitation of all those prior works was that the subjects recruited were not particularly experienced in barefoot running. Runners not accustomed to running barefoot could have their natural foot structure weakened by long-term footwear use and their proprioceptive sensitivity may be reduced [21]; therefore, they could be less effective in adapting their running style when running in this condition.

A thorough search of the current scientific literature revealed that there is no published research investigating differences in habituated and non-habituated subjects, as most studies have used initial responses of habitually barefoot runners for their investigations [2,6,8]; however, several studies showed that habitually shod runners run differently from habitually barefoot runners [2,4,6,10]. Still, it remains uncertain how long the habituation period should be for habitually shod runners to make a safe transition into simulated barefoot running.

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Previous studies attempted changing the running motor patterns and running kinematics through strength, neuromuscular interventions, or plyometric, within 6–9 weeks in duration [9,22,23]. A 6-week program was selected for our study to allow preliminary adaptation of musculoskeletal structures to different impact forces, with the purpose of decreasing the risk of injury from too-rapid transition [13,14,24]. Subsequently, higher SBR training loads could be gradually introduced to induce a training effect. Therefore, the current study investigated the effects of a 6-week transition program of SBR on the stance-phase kinetics in habitually shod female runners when compared with the same group in a non-habituated state, and thereby to investigate acute and the chronic changes in this group.

Material and Methods

Subjects

A total of 12 female runners – mean (±SD) age 25.7±3.4 years; height 162.2±7.7 cm; body weight 59.4±6.9 Kg, and body mass index 22.5±1.2 Kg/m^2 – volunteered to participate in the study. Inclusion criteria were no prior history of joint injury or surgery, and no medical conditions affecting the connective tissue. All subjects were heel-strikers free of any obvious malalignment or injuries at the time of data collection. Running in standard cushioned shoes prior to the beginning of the study involved the neutral and anti-pronation type models. All our subjects were recreational runners accustomed to running 3–5 days per week and an average 25 km per week for at least for the last 6 weeks, with the intention of remaining at a similar intensity for the following 6 weeks. Subjects were excluded if they had any lower-limb injuries that had prevented them from running in the last 6 months; had been treated in a rehabilitation program for the lower limb; or had experienced minimalistic or SBR running. The study was approved by the Ethics Committee of Loma Linda University. Written informed consent was obtained from all subjects prior to enrollment.

Electromyography

Electromyography (EMG) activity was measured from the tibialis anterior (TA) and the lateral gatstroceniums (GAS). These muscles were selected for their synergistic action. Prior to electrode placement, the skin was lightly abraded and cleaned with alcohol. Circular pre-gelled 10-mm bipolar Ag-AgCl surface electrodes (EL503; Biopac Systems, Inc., Goleta, CA) were placed in parallel on the belly of each muscle in alignment with the direction of the muscle fibers and the distal tendon of each muscle with a 20-mm inter-electrode distance (according to standards provided by Seniam.org). For the TA muscle, the electrodes were placed about 15 cm below the center of the kneecap on the upper third of the TA muscle [25]. The GAS electrode location was centrally placed in a lateral fashion distal from the midpoint of the belly to the tendinous junction. A reference electrode for the EMG system was placed over the tibia. All electrodes were placed by a single experimenter to insure consistency thorough the study. Electrodes and telemetry amplifiers were secured to the skin using medical tape to minimize movement artifacts and to prevent the electrodes from losing surface contact due to sweating. Maximum voluntary contraction test were conducted for each subject. The MVC tests for the TA and LG muscles were performed while the subjects were in a sitting position with the knee flexed at 90°. The subject was instructed to perform three 5-s maximum voluntary isometric contractions for each selected muscle against the resistance of the same tester and was given verbal encouragement while doing so. The middle 2 seconds of the MVCs of each contraction were analyzed. A 3-min rest period was allocated between each contraction. Surface EMG was recorded using a device made by Biopac Inc. (Goleta, CA), Acknowledge 4.3.1. The electromyography was recorded using a sampling rate of 2000 Hz through a 24-bit A/D converter. The raw data were processed using a band-pass filter (15–150 Hz). The EMG was integrated then divided by the maximum voluntary contraction (MVC) to normalize the EMG activity of very participant. Muscle activities were analyzed by the by the method described by Shih et al. [26], in the following conditions: (A) the pre-activation phase: 50 ms before foot landing until foot landing, (B) the impact phase, and (C) the peak push-off phase (Figure 1A, 1B). The EMG activity of the selected group of muscles were synchronized with a High Frame Rate Camera (CAM-HFR-A) SVHS Sony video camera (Basler, Biopac Systems, Inc., Goleta, CA) to capture the running phases as series of videos at 100 FPS (640×480 resolution). The camera was mounted on a tripod placed 2 m from the treadmill and aligned so the plane of the camera was parallel to the treadmill. The camera was leveled using the bubble level attached to the tripod and set to the height of the subject's knee during running.

Ground reaction force

Runners ran on an instrumented treadmill (Zebris FDM; Zebris Medical GmbH, Allgäu, Germany) at 10 km/h. The treadmill had an embedded pressure mat containing more than 15 000 pressure sensors from which data were integrated to produce the vertical ground reaction force. Once the runners demonstrated a stable running pattern, data were sampled at 100 Hz for 60 s. The variables of interest – vertical impact peak (IP), active peak (AP), vertical instantaneous loading rate (VILR), and vertical average loading rate (VALR) – were extracted from the processed data and were obtained by the method described by Crowell and Davis [27].These early impact variables were chosen for their demonstrated association with various running injuries [28–30]. The IP was the local maximum between

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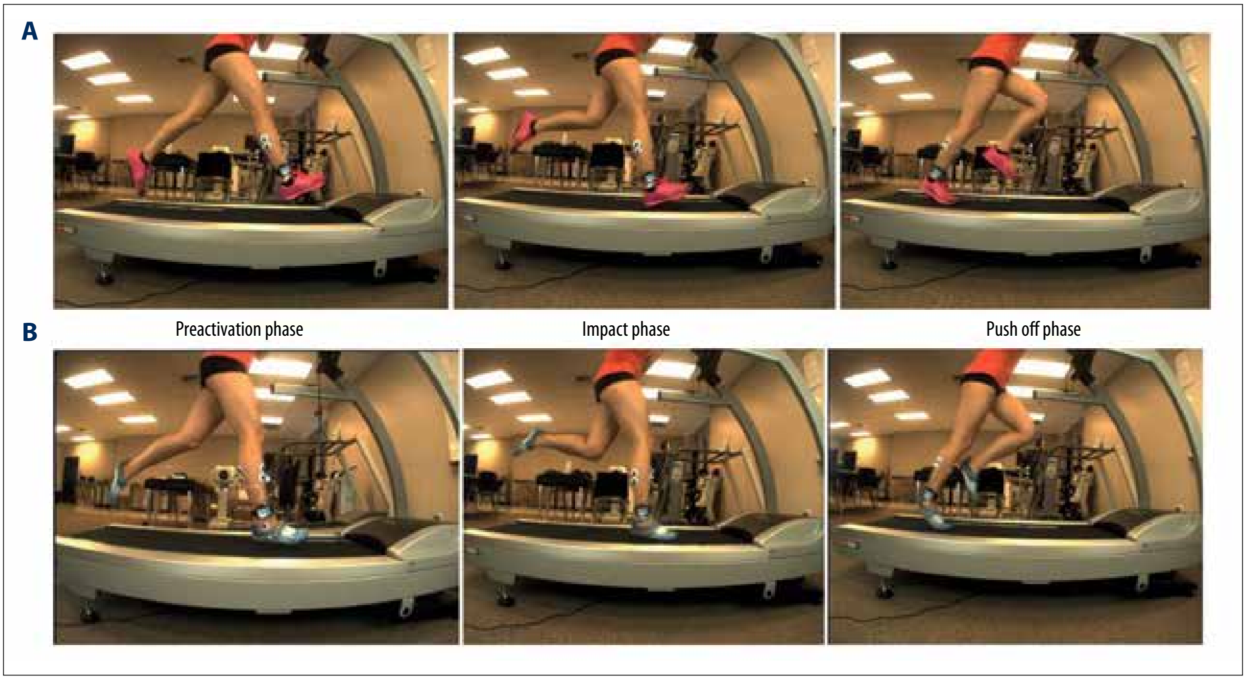

Figure 1. (**A**) Phases of running during shod running with RFS pattern. (**B**) Phases of running during simulated barefoot running with FFS pattern.

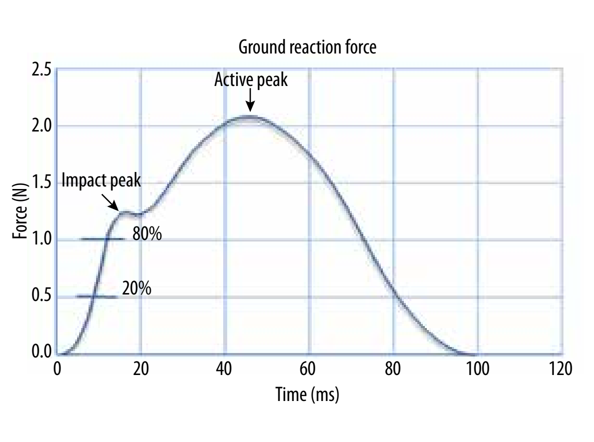

Figure 2. Ground reaction force curve showing the variables of interest: IP, AP, VILR and VALR. Note that both vertical loading rates (VILR and VALR) were calculated in the region from 20% to 80% before the impact peak.

foot-strike and maximum force on the vertical ground reaction force curve; it usually occurred within the first 50 ms of stance phase (Figure 2). The VILR was the maximum slope of the vertical ground reaction force curve between successive data points in the region from 20% to 80% of the VIP (Figure 2). This was the most linear portion of the curve in the early part of stance. The VALR was the slope of the line through the 20% point and the 80% point. Therefore, all variables were associated with the impact phase of running. The data were processed and averaged for each subject. All stance phases were extracted from data and transferred to Matlab for processing using a custom-written MATLAB program (V8.3 R2014a, Math Works, Inc., Natick, MA, USA). Temporal information for heel-toe latency was used to compute the gait attributes (IP, AP, VALR, and VILR) for each stance phases, and averages were computed for data analysis. To visualize, the GRF data were normalized to 0–100% of the stance phase (Figure 2).

Protocol

Subjects were evaluated pre- and post-intervention while running at (10 km/h) on a conventional instrumented treadmill (Zebris FDM; Zebris Medical GmbH, Allgäu, Germany) in both simulated barefoot and shod conditions. This velocity was selected to represent a comfortable running pace for recreational runners, and to compare with the results of other studies that had evaluated barefoot and shod running kinematics at similar velocities [4–6]. All subjects came to our laboratory for 3 identical testing sessions separated by the 6-week habituation period in addition to the training sessions. Test conditions were the same in all conditions and took place indoors in a temperature-controlled area with artificial lighting. Subjects avoided strenuous exercise in the 24 h pre-test and warmed-up according to their usual routines. All subjects wore standard, cushioned shoes for the shod running. After the placement of the EMG electrodes, subjects ran at a self-selected velocity for at least 4 min to feel comfortable running on a treadmill. After 4 min, treadmill velocity was increased to 10 Km/h before a data collection period (duration 60 s). Data was collected for

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Table 1. Running technique guidelines.

Keep stride short and increase cadence [2,21]
Land as light and as quiet as possible [27]
Land on the forefoot, allowing heel to contact immediately afterwards [49]
Keep hips forward and head up [2]

Table 2. Exercise program.

Running form drills	• Forefoot Striking • Increase cadence • Shorter step length
Proprioceptive exercise	• Single-leg stance
Flexibility exercise	• Calf stretching against wall • Calf stretching off the edge of a step
Strengthening exercises	• Foot intrinsic • Doming and hopping drill • Toe grabs • Single-leg raises (calf raises)
Polymeric activities	• Hops (single-leg forward hops) • Squat jumps

60 s at the 5th min of running, allowing enough time above the 4 min that has been suggested to be required to optimize leg stiffness and running technique, depending on surface and shoe hardness [31]. Given that endurance running involves repetitive impacts, a long sample period of 60 s was selected to more adequately represent average loading over a longer period of time. Stride frequency was calculated by the number of steps that occurred on the right foot during the 60 s. The entire testing protocol was repeated again after a single training session in non-habituated SBR condition and following the 6-week habituation period of SBR (post-tests). During the post-tests, subjects were reminded before testing commenced to concentrate on running technique, but were given no feedback while running, in order to maintain technical consistency. All subjects expressed comfort with treadmill running with the attached EMG electrode before data collection and were not aware of when kinematic data was being captured.

Interventions

The intervention is this study was instruction and training to adopt a forefoot strike running technique. Familiarization took place in Vibram "FiveFinger" Bikila LS (VFF; Vibram®, MA, USA) minimal footwear. Immediately after pre-tests, each subject was provided with a structured progression of SBR over a 6-week habituation period and relevant injury prevention exercises. Running technique guidelines were also provided based on current findings in the literature (Table 1). Both the technique changes and exercises were fully demonstrated (Table 2). The program incorporated SBR running into the subject's normal training routines (increasing from ~10% to ~25%) [32], which required that the SBR running took place at the beginning of any training session, and then subjects were allowed to continue their normal training load in their own preferred conventional running footwear. Thus, subjects would gradually increase exposure to SBR during this period, while also maintaining the remainder of their training schedule in conventional running shoes. Each subject was provided with detailed guidelines, including a structured progression of SBR over the 6-week habituation period (Tables 1, 2). The program, which included visual feedback and instruction on technique, simply asked subjects to run in the simulated barefoot condition at a comfortable velocity and to include specific training drills and exercises designed to teach forefoot striking consisting of weight shifting, falling forward, foot tapping, and high hopping, as described previously [22,33]. Additional emphasis included using the hamstrings muscle group to pull the foot from the ground versus push the foot off the ground using the gastrocnemius and soleus muscles [33]. The subjects also practiced running barefoot and were provided with verbal cueing to ''run quietly'' to eliminate the tendency to heel strike upon ground contact. A video camera was used to record individual running form to demonstrate forefoot technique running errors (e.g., heel-striking, over-striding). Exercise instruction was conducted 3 times per week for approximately 25 min each session for the first week. A typical training session during the first week consisted of approximately 15 to 20 min of the specific training drills, followed by forefoot running practice for distances of 0.25 km. The verbal cueing and video camera were used during the running practice time. The rationale for adopting this approach was to prepare the lower extremity for safe transition for a forefootfoot stike pattern because most of the typical deficits encountered were weak calf, reduced subtalar joint dorsiflexion, and inhibition/ weakness of foot intrinsic muscles.

Data analysis

A 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=12 would provide a statistical power of ~80% (G*Power v3.0.10 free software). Descriptive statistics for variables and measures of central tendency for continuous variables were calculated to summarize the data. A Kolmogorov-Smirnov normality test proved all variables to be normally distributed. Repeated-measures ANOVA was used to evaluate the primary outcome variables of the EMG activities. The post hoc Bonferroni test was used to analyze differences between pre-intervention, non-habituated SBR and after 6

Table 3. Means and standard deviations of the IEMG of TA and GAS.

	Shod running Mean ±SD	Non-habituated SBR Mean ±SD	Habituated SBR Mean ±SD
Pre-activation TA	55.37±10.25[a]	54.14±7.69	15.52±3.77
Pre-activation GAS	18.63±4.70[a]	26.05±8.89*	60.02±11.32
Stance phase TA	27.15±10.22[a]	18.64±4.97	13.36±6.26
Stance phase GAS	46.40±16.07[a]	42.25±7.98	77.42±8.57
Push-off of TA	13.12±6.25	11.35±5.27	11.80±5.66
Push-off of GAS	68.31±13.76[a]	64.37±8.95	53.92±4.51

TA – tibialis anterior; GAS – gatstroceniums; SBR – simulated barefoot running. [a] Significant different from habituated SBR; <0.05. * Significant different from non-habituated SBR; P<0.05. SD – standard deviation.

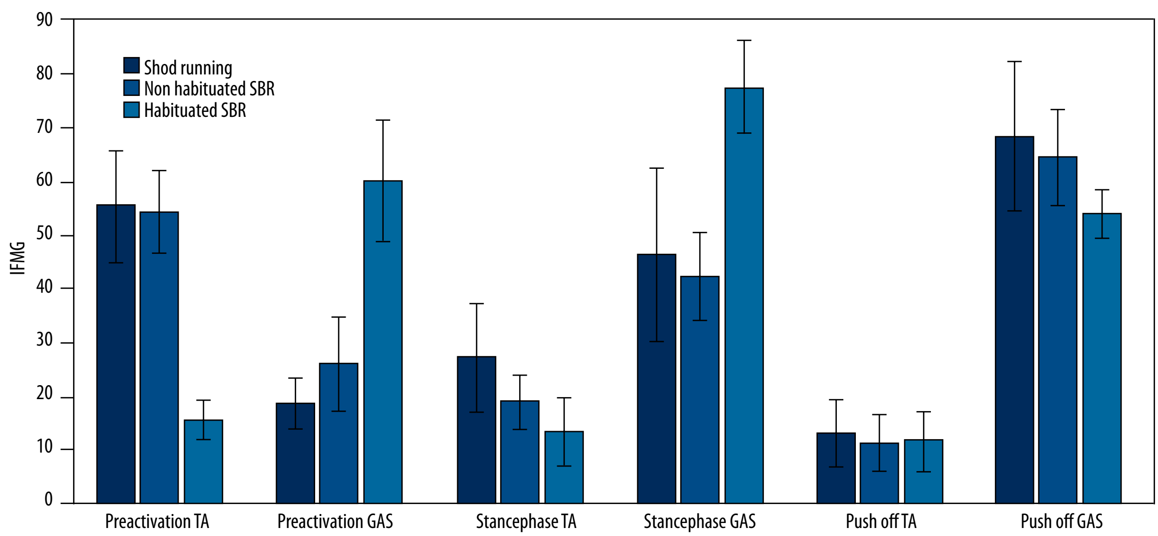

Figure 3. Integrated EMG of the tibialis anterior (TA) and gastrocnemius (GAS) muscles during different phases of running during shod running, non-habituated simulated barefoot running (SBR), and habituated simulated barefoot running.

weeks habituation SBR. A paired t test was used to evaluate the difference in the biomechanical variables (stride length, stride frequency, vertical GRF, and rates of loading) between the shod and habituated simulated barefoot running conditions. The level of significance was set at P level of.05. All statistical analyses were performed using SPSS statistics software (Version 20).

Results

Electromyography

EMG amplitudes of the tibialis anterior and gastrocnemius during the pre-activation phase showed a significant difference between foot-striking pattern in both shod running and habituated SBR (Table 3, Figure 3). Amplitudes of the GAS in the pre-activation and stance phases showed significant higher activity in habituated SBR compared to shod condition (60.02±11.32 *vs.* 18.63±4.70, respectively). No statistical difference was observed concerning the TA muscles for the pre-activation amplitudes between the shod condition and non-habituated SBR. However, a significant difference was detected in the pre-activation amplitude of the GAS between the shod condition and non-habituated SBR. Moreover, concerning the stance and push-off phases, there was no significant statistical difference between the SBR and the SR for both groups of muscles (Table 3, Figure 3).

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Table 4. Means and standard deviation of the spatiotemporal and kinetic variables.

	Shod running Mean ±SD	Habituated SBR Mean ±SD	P value*
Vertical average loading rate (BW/S)	38.33±5.01	24.27±4.09	<0.001[a]
Vertical instantaneous loading rate (BW/S)	61.20±9.46	40.11±7.43	<0.001[a]
Impact peak (BW)	1.39±0.47	0.60±0.14	<0.001[a]
Active peak (BW)	1.94±0.18	1.98±0.20	0.452
Stride length (m)	1.76±0.19	1.59±0.21	<0.001[a]
Stride frequency (steps/sec)	2.69±0.13	2.80±0.10	<0.001[a]
Step time (s)	0.38±0.02	0.35±0.02	0.053[a]
Contact time (%)	56.14±4.33	40.85±5.40	0.021[a]
Flight time (%)	43.77±4.30	59.05±5.26	0.042[a]

* Paired t test; [a] Significant difference; AVLR – average vertical loading rate; VILR – vertical instantaneous loading rate; BW – body weight; BW/S – body weight per second; s – second.

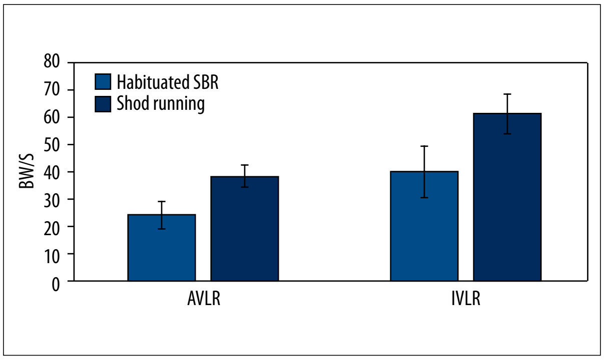

Figure 4. Average vertical loading rate (AVLR) and instantaneous vertical loading rate (IVLR) during pre-intervention shod running and post-intervention 6 weeks of simulated barefoot running (SBR).

Ground reaction force

A comparison of the pre-intervention and post-intervention results revealed that both VALR and VILR were significantly reduced during habituated SBR running compared to shod running. The rate of loading is calculated as 20–80% of the impact transient (when present) or to (3–12%) of stance phase when impact transient is absent [34]. The average vertical loading rate for habituated SBR runners was (24.27±4.09) body weights per second, which was significantly lower than that of shod runners (38.33±5.01, P<0.001) (Table 4, Figure 4). Magnitude of impact force was significantly lower during SBR running compared to shod running. The impact force was 0.60±0.14 body weight in barefoot runners, which was significantly lower than the 1.39±0.47 (P<0.001) body weight in shod runners (Table 4).

Spatiotemporal variables

A significant difference of the spatiotemporal variables (stride length, stride frequency, step time, contact time, and flight time) was detected between shod and habituated SBR conditions. The stride length was significantly lower during SBR compared to shod condition (1.59±0.21 *vs.* 1.76±0.19 m, P<0.001). The stride frequency in habituated SBR was significantly greater than shod running (2.80±0.10 *vs.* 2.69±0.13 steps/push-off sec, P<0.001). As a consequence, step time was significantly decreased when running barefoot.

Discussion

To the best of our knowledge, few authors have examined barefoot running and none of them have reported a biomechanical and muscular analysis of the differences between shod running and barefoot running after habituation. This is the first study to investigate the effect of 6-week habituation of SBR training on running kinetics. The results of the current study showed that the 6-week intervention of controlled SBR training was enough to induce significant changes in kinetics of the lower limb during barefoot running.

Studies over the past 2 decades have provided strong evidence that continued practice of a task (training) facilitates neuromuscular adaptations, which are characterized by more skilled control of movement and muscle recruitment patterns [35,36]. Training-induced adaptations of descending motor commands reflect learning within the CNS and can be represented by

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changes in muscle electromyography (EMG) function (motor recruitment) [36]. Like training, passive interventions such as shoes and in-shoe orthoses [37,38] have been shown to induce acute adaptations in motor recruitment.

From the neurophysiological perspective, it is well-acknowledged that the innervation activity during running cycle consists of 3 phases: the pre-activation phase (starting before ground contact), the activation phase (during weight-acceptance), and the innervation phase (during push-off).

The main finding in the present study is that 6 weeks of habituation to SBR induces neuromuscular changes in TA and GAS muscles activation pattern during different phases of running. The EMG activity of the TA was found to be significantly more activated during the stance phase of shod condition when compared to the habituated SBR condition. The integrated EMG value during the 50 ms prior to foot-strike was highest during pre-activation shod running and the lowest during habituated SBR. Additionally, a significant increase in pre-activation of the gastrocnemius muscle was observed during habituated SBR compared to shod running, which supports the reduction of heel impact observed by changing to a forefoot strike pattern.

The EMG recruitment patterns for simulated barefoot running are less documented in the literature. Only 3 studies compared EMG signals between barefoot and shod running [21,26,39]. Our findings support the results of the previous literature that reported a greater recruitment of GA in the pre-activation phase in the shod condition when compared to non-habituated barefoot running condition [21]. However, our results did not show a significant statistical difference in the EMG activities of the TA for the pre-activation, stance, and push-off phases between the non-habituated SBR and shod conditions. In agreement with our findings, Divert et al. reported no significant difference in pre-activation levels of the tibialis anterior when comparing non-habituated barefoot and shod running [21]. EMG activity of the TA showed a high recruitment of muscular activity before and after heel strike. TA EMG intensities for shod running showed a greater activation 50 ms before impact compared to the weight-acceptance phase of shod running. The activity before heel strike keeps the ankle dorsiflexed and tunes the muscle for the anticipated impact. This muscular activity must be released quickly at impact to plantar flex the ankle.

Indeed, EMG activity before heel strike is pre-programmed based on the anticipated impact shock. Just before ground contact, muscle activity has a crucial role in preparing the locomotor system for the landing and the subsequent ground impact [38]. The required protection from repeated shock of the muscular skeletal structure could lead to a higher pre-activation of plantar flexor muscles. It is also worth noting that higher active pre-stretch levels [40], as well as the decrease of contact time [41] seen during SBR, could improve the stretch-shortening cycle behavior of the plantar flexor muscles and therefore possibly allow better storage and restitution of elastic energy [42,43] compared to shod running.

The most favorable difference between SBR and shod running is the significant reduction in impact transient and the loading rate in the SBR barefoot condition. This is deemed significant because the magnitude of this impact transient has been correlated with the risk of running injuries [2]. In the present experiment, SBR running was characterized by decreased loading rates and impact forces. The significant lower values of impact forces and loading variables (VILR, VALR, VIP and AP) observed in SBR compared to the shod running conditions are in line with previous studies. Divert et al. reported similar results of significant different amplitudes between barefoot and shod condition [21]. In contrast, no significant difference was observed by De Wit et al. for running speed 3.5 and 5.5 m/s and by Dickinson et al. in 6 subjects running across a force plate [4,44]. In both of those works, impact force amplitudes were considerable higher than those recorded in our study. Many methodological differences may explain the divergent results. Firstly, the subjects of the previous studies were not accustomed to running barefoot and this could have reduced their ability to dampen the forces elicited at impact while barefoot. According to Robbins et al., adaptation to barefoot running could take several weeks [7]. Furthermore, the subjects run in a lab runway and a limited number of steps were analyzed. As suggested by divert el al, it is possible that when data are collected on a limited number of steps, runners are able to sustain and then maintain high impact forces [21]. In contrast, a habituation period, as experienced by our subjects, would lead the runners to adopt strategies to reduce stress under the heel.

When running barefoot, step duration, stride length, and flight time were significantly shorter, and stride frequency was significantly higher, than in the shod conditions. Stride frequency is inversely proportional to step duration multiplied by velocity, and velocity was controlled in this study. Thus, it would be expected that if one variable increased, the other should decrease, and vice versa, as was recorded in the present study. An increased contact time when shod might be may be partially attributable to the mass of the traditional shoe [21]. Stride frequency when running barefoot has been compared with running in traditional shoes by Divert et al. and Squadrone and Gallozzi [6,45]. Our study and that of Squadrone and Gallozzi both reported significantly higher stride frequencies in the barefoot condition [6]. We hypothesized that the biomechanical adjustment observed in stride kinematics could help to limit the larger impact forces that should be absorbed by the

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muscular skeletal system at each step. The hypothesis that further changes would occur in barefoot kinetics was supported by significant changes in the EMG activities of the TA and GAS after 6 weeks of SBR.

Of particular note is that the validity of the previous body of work is compromised by the lack of evaluation after habituation, or re-training, of previously shod rearfoot-striking runners to barefoot forefoot-striking running styles. While future research may standardize the transition protocol, this should be done carefully because individuals progress differently, and higher injury rates may result from enforcing progression. The current study was limited to recreational female runners. Consequently, one should be cautious of generalizing the results to highly trained athletes, whose running mechanics may be extremely consistent [5,10,46]. Care should also be taken when comparing kinetic data from this study with that of studies in which subjects experienced running at higher velocities [2,10,12].

Limitations

We acknowledge limitations of the present study. Treadmill gait and over-ground gait are not identical [2,47]. However, treadmill usage allowed subjects to be familiarized with each condition and reach a stable state in their stride pattern before data acquisition occurred. Not knowing when data would be acquired also had other potential benefits when compared with over-ground testing and use of force-plates [48]. The lack of standardization of the traditional shoes used may have impacted the results in the shod condition. Participants were tested in their regular training shoes to most accurately represent the normal running mechanics exhibited in training. For the transition program, SBR training protocol was prescribed according to the total training volume to simplify the protocol and encourage compliance. This, however, makes it harder to quantify the "dose" of the intervention received by each subject or the amount of SBR training as an amount of total training capacity for each subject.

Conclusions

The findings of this study showed that changes in motor patterns in habitually shod runners are possible and can be achieved within 6 weeks. Six weeks of habituated SBR led to significantly decreased activity of the tibialis anterior in the pre-activation and absorptive phase of stance and may reduce higher risk of running injuries (e.g., chronic exertional compartment syndrome). Habitually shod runners did not automatically alter their landing patterns from heel strike to a non-heel strike pattern during early exposure to barefoot running. During non-habituated SBR, subjects did not experienced neuromuscular adaptations they experienced after 6 weeks of habituation. However, the neuromuscular adaptation was influenced by the habituation period. Therefore, a gradual transitioning program with real-time kinetic feedback and evaluation is recommended.

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