South African Journal for Research in Sport, Physical Education and Recreation, 2013, 35(1): 153-164.
Suid-Afrikaanse Tydskrif vir Navorsing in Sport, Liggaamlike Opvoedkunde en Ontspanning, 2013, 35(1): 153-164.
ISBN: 0379-9069

BAREFOOT RUNNING CAUSES ACUTE CHANGES IN LOWER LIMB KINEMATICS IN HABITUALLY SHOD MALE RUNNERS

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ABSTRACT

The purpose of this study was to compare differences in knee and ankle kinematic and spatio-temporal variables at foot strike between barefoot and shod running. Twelve male runners (age 21.6±1.26 years) performed six running trials in each running condition on a 12m indoor runway at a self-selected pace. Lower limb kinematics and spatio-temporal variables were recorded with a six-camera T10 Vicon motion capture system (200Hz). In the barefoot condition runners landed with significantly greater knee flexion ($p<0.01$; ES=2.61) and less ankle dorsi-flexion ($p<0.05$; ES=1.12) compared to in the shod condition. No significant differences were found between knee varus/adduction (ES=0.78) or ankle inversion/adduction (ES=0.85) between the barefoot and shod conditions. The barefoot condition had significantly shorter contact time ($p<0.01$; ES=1.99) and step time ($p<0.05$; ES=1.13), while significantly higher step frequency ($p<0.05$; ES=1.25) compared to in the shod condition. Results indicated that immediate adaptations occurred when transitioning from shod running to barefoot running.

Key words: Barefoot running; Kinematics.

INTRODUCTION

Running has become a popular training modality and is currently considered to be one of the most important recreational activities, which not only improves overall fitness, but also provides numerous other health benefits (De Wit *et al*., 2000; Squadrone & Gallozzi, 2009). This increase in popularity has led to a greater number of runners suffering from overuse injuries as a result of impact forces at foot strike, with the ankle and knee joints as the most affected locations (Taunton *et al*., 2002; Braunstein *et al*., 2010; Sakurai & Maruyama, 2010). Both footwear and running surface have been shown to influence the foot/shoe-ground interface, of which footwear has received most attention (Hardin *et al*., 2004; Smith *et al*., 2010). Historically, runners were either barefoot or wore minimal footwear, with the modern running shoe only being invented in the 1970’s (Lieberman *et al*., 2010).

According to Griffin *et al.* (2007), the running shoe is the most important piece of equipment for a runner. Running shoes are thought to provide benefits in human locomotion, such as protection, rear foot control, cushioning, attenuation of impact forces and heel stabilisation during activity (McNair & Marshall, 1994; McPoil, 2000; Divert *et al*., 2008; Lieberman *et al*., 2010). However, research has failed to confirm the frequently claimed ability of running shoes to protect runners from injury, and even with the use of orthotics and increased cushioning, the incidence of running injuries remains high (Hart & Smith, 2008; Bacon *et al*., 2010). It has been suggested that running shoes may be a key factor leading to running injury (Hreljac, 2004; Bacon *et al*., 2010). Possible causes of injury may include abrupt collision forces (Hart & Smith 2008; Lieberman *et al*., 2010), limited proprioception (Robbins & Gouw, 1991) and over-pronation of the foot at heel strike (Clarke *et al*., 1984; Stacoff *et al.*, 1988). Barefoot running is viewed as the foundation for normal running (Clarke *et al*., 1984) and some authors suggest that habitual barefoot running could prevent impact related injuries (Stacoff *et al.*, 2000; Lieberman *et al*., 2010).

Some coaches have made use of barefoot training as it is thought to provide a means for the foot to more naturally interact with the ground, improve musculoskeletal strength, train both intrinsic and extrinsic foot muscles and assist in force attenuation (Robbins & Hanna, 1987; Brüggermann *et al.,* 2005; Kersting & Brüggermann, 2006; Smith *et al*., 2010; Weimar*et al*., 2010). According to Hart and Smith (2008), barefoot running increases perception of surface variations. This enables a greater variation of tendons, ligaments and motor units to be recruited with every foot strike, leading to more specific responses to the running surface (Hart & Smith, 2008). Several authors have stated that running barefoot can be viewed as a condition where prominent changes in running style, such as shorter step lengths, flatter foot placements and greater knee flexion contact angles could be expected (De Wit *et al.,* 2000; Divert *et al.,* 2005; Squadrone & Gallozzi, 2009).

Alterations in lower limb and spatio-temporal kinematics are speculated to influence the kinetics of runners and possibly reduce the risk of overuse running injuries. According to De Wit *et al*. (2000), the horizontal distance moved during the stance phase, is less while running barefoot compared to shod. Decreasing stride length while running has been marked as a potential mechanism to reduce bone strain and tibial stress fractures in runners (Edwards *et al.,* 2009). Along with touchdown velocity and the material properties of the landing surface (heel-pad, shoe, ground), impact forces are largely determined by initial footstrike angles of the knee and ankle (Gerritsen *et al*., 1995). Derrick (2004) suggested that this greater knee flexion observed at footstrike, could be an effort to decrease excessive impact forces and the potential for injury. Landing with more ankle plantar-flexion and knee flexion has been shown to reduce vertical impact peaks and loading rates in habitually barefoot runners (Squadrone & Gallozzi, 2009; Lieberman *et al*., 2010). Subsequently, higher vertical loading rates have been associated with overuse injuries, such as tibial stress fractures (Grimston *et al*., 1993; Ferber *et al*., 2002; Milner *et al*., 2007), and plantar fasciitis (Pohl *et al*., 2009), in runners.

While those accustomed to barefoot running appear to have several benefits with regard to diminished impact peaks and delayed vertical loading rates (Squadrone & Gallozzi, 2009; Lieberman *et al*., 2010), there are still many unanswered questions as to whether these benefits are easily transferable to habitually shod runners. Specifically, it is not known if all habitually shod runners will immediately and naturally learn the correct barefoot running kinematics. Robbins and Gouw (1991), stated that when habitually shod subjects run barefoot, they might experience discomfort under the plantar surface of the foot and thus generate sufficient shock-moderating behaviour equal or greater than while running shod due to enhanced sensory protection. Similarly, Kurz and Stergiou (2005) speculated that altered coordinative strategies while running barefoot may be linked to the high perceived impact through the mechanoreceptors of the foot. These perceptions may lead to a flatter foot position to reduce the local pressure under the heel, as ground contact is covered by larger surface areas (De Wit *et al*., 2000). However, the majority of runners have accommodated to heel striking in modern day footwear (Hasegawa *et al*., 2007). Additionally, Lieberman *et al*. (2010) found that 83% of habitually shod runners will maintain a heel strike landing when running barefoot under acute conditions. The same paper by Lieberman *et al*. (2010) also mentioned that heel striking while barefoot, resulted in impact force magnitude and loading rates that are significantly higher compared to the shod condition. This suggests that some newly transitioned runners are not able to anticipate higher impact under the heel, while running barefoot and thus not able to make the necessary kinematic adjustments to decrease impact loads. These greater magnitudes and rates of impact forces could be detrimental and could place runners at risk for overuse injuries (Grimston *et al.,* 1993; Ferber *et al.,* 2002; Milner *et al.,* 2007; Pohl *et al.,* 2009).

PURPOSE OF THE STUDY

With the above considerations in mind, more research is needed to shed light on whether habitually shod runners maintain the typical shod running kinematics while under acute barefoot running conditions. Thus, the primary aim of the study was to compare the acute kinematic differences between barefoot and shod running conditions in habitually shod runners, with a focus on how alterations in the mechanical characteristics of foot/shoe-ground interface affect both the sagittal plane and frontal plane kinematics and spatio-temporal variables of the lower extremities. Based on the evidence shown by Lieberman *et al*. (2010), it was hypothesised that most runners would not adapt their lower limb kinematics due to acute barefoot running on hard surfaces.

METHODS

Participants

Twelve healthy, male recreational runners (age 21.6±1.3 years; height 1.8±0.05m; body mass 77.2±10.2kg; BMI 23.8±2.6kg/m^2) participated in the study. All participants were free from musculoskeletal injuries, running related injuries or any other conditions that would affect running gait within the previous 6 months prior to testing. Additionally, participants were excluded from the study if they had any history of foot orthotics. All participants were habitually shod runners, played sport at club level and ran between 20 and 40km per week. A few of the participants had some experience in barefoot sport (beach touch rugby), however, none of these sporting activities occurred within 3 months prior to testing. All runners received written and verbal information on the study and completed an informed consent document before participation.

Data capturing procedures

All testing and measurements were conducted in the Motion Analysis and Physiotherapy Clinic at the medical campus of the university. Kinematic data of the lower extremities were captured using a six-camera T-10 Vicon three-dimensional motion capture system (Oxford Metrics Ltd., Oxford, UK) with Nexus 1.4 116 software, at 200Hz.

Anthropometric measurements were obtained according to standard procedures by the same laboratory technician (Certified level one anthropometrist, ISAK). Anthropometric measurements of the lower body with the participants in the standing position included leg length (defined as full leg length, measured between the ASIS marker and the medial malleolus, via the knee joint), knee width (defined as the medio-lateral width of the knee across the line of the knee axis), and ankle width (defined as the medio-lateral distance across the malleoli). A total of 35 reflective markers (14mm in diameter), were placed on the body according to the standard plug-in gait model. Specifically, 16 of the markers were used to record data of the lower body, which defined the 3D kinematics of the pelvis, and the left and right thighs, shanks and feet. Markers of the lower body were placed on the sacral (on the skin mid-way between the posterior superior iliac spines (PSIS) and positioned to lie in the plane formed by the ASIS and PSIS points); and left and right ASIS (left anterior superior iliac spine), PSIS (left posterior superior iliac spine immediately below the sacro-iliac joints, at the point where the spine joins the pelvis), thigh (over the lower lateral 1/3 surface), knee (on flexion-extension axis), tibia (over lower 1/3 surface), ankle (on the lateral malleolus along an imaginary line that passes through the trans-malleolar axis), heel (on the calcaneous at the same height above the plantar surface of the foot as the toe marker), and toe (over the second metatarsal head, on mid-foot side of the equinus break between fore-foot).

The different running conditions were performed barefoot and in the participants' own running shoes for the most typical performance (Queen *et al*., 2006; Morley *et al*., 2010). Running conditions were selected in a randomised order for each subject. Rest periods between running conditions were between 2 to 3 minutes. Over-ground running on a 12m indoor runway was selected. The measurement volume was specifically 6m long, 3m wide and 2m high. Although this might be a large volume, marker visibility during the recorded 2 steps was unaffected. Participants performed 3 practice runs for familiarisation. Each participant was instructed to run at a self-selected pace, which has been shown to improve consistency and enhance repeatability in kinematic variables (Masani *et al*., 2002; Queen *et al.*, 2006). In addition, the runners were encouraged to maintain a steady speed for the running conditions. Five trials of each running condition were recorded and used for analysis. For each running trial the sum of 2 consecutive steps (one complete gait cycle), which fell within the area of the visual field was used for data analysis. Thus, 5 complete gait cycles for each participant were analysed per running condition (10 gait cycles per subject).

Means for both left and right steps were used in the analysis (Titianova *et al*., 2004). Participants were instructed to circle around and run continuously with each trial of a specific condition, without stops. After all the trials were captured, each trial was reconstructed and labelled. Possible gaps in the data were filled using either the spline- or pattern-fill options: if the gaps were smaller than 4 frames the spline-fill was used, if the gap was bigger than 4 frames pattern-fill was used. Once this was completed, the Dynamic Plug-in gait pipeline was run. Kinematic data were processed through Vicon Work station's Woltring filter (MSE=20mm). Mean values for each variable were then calculated, followed by calculation of group mean values. With the absence of kinetic data, foot strike was determined as: horizontal velocity below tolerance (30mm/sec) + vertical downward velocity below tolerance (30mm/sec), depending on which marker (heel or toe) contacted the ground first. Lower limb kinematic variables of interest included: spatio-temporal variables, step length (m), step frequency (steps.min^{-1}), and contact time(s); sagittal plane lower limb kinematics (knee flexion (°) and ankle dorsi-/plantar-flexion (°) at foot strike; and frontal plane lower limb kinematics (knee varus/adduction) (°) and ankle inversion/adduction (°) at foot strike.

Statistica Version 10 (StatSoft, Inc., Tulsa, OK, 2010), was used for data analysis. Independent t-tests were used for all kinematic and spatio-temporal variables. The level of significance was set at $p < 0.05$. Effect sizes (ES) were calculated between conditions (Cohen, 1990). Data are presented as group means and standard deviations.

RESULTS

The mean self-selected running speed of the subjects at foot strike was 3.63 ± 0.08m.s^{-1}. No significant differences were found in running speed between the different conditions ($p = 0.75$; ES=0.33 for barefoot vs. shod). This finding could exclude running speed as a confounding variable (Dugan & Bhat, 2005).

***TABLE 1*: MEANS±S FOR SPATIO-TEMPORAL VARIABLES AND KNEE AND ANKLE JOINT KINEMATICS AT FOOTSTRIKE (DEGREES) BETWEEN BAREFOOT AND NORMAL SHOD RUNNING**

Variable	Barefoot	Shod	p-Value	ES
Step time (s)	0.353 ± 0.02**	0.371 ± 0.02	0.01	1.13##
Contact time (s)	0.210 ± 0.02**	0.246 ± 0.02	0.0001	1.99###
Step length (m)	1.28 ± 0.09	1.36 ± 0.14	0.10	0.65
Step frequency (steps.min^{-1})	170.42 ± 8.83**	161.00 ± 6.09	0.008	1.25##
Self-selected running Speed (m/s^{-1})	3.64 ± 0.26	3.53 ± 0.42	0.45	0.33
Ankle dorsi-flexion at footstrike (°)	1.64 ± 4.54*	7.87 ± 6.81	0.02	1.12##
Knee flexion at footstrike (°)	18.79 ± 3.02**	11.05 ± 3.18	0.0000	2.61###
Knee varus/adduction at footstrike (°)	6.76 ± 2.62	2.78 ± 1.04	0.08	0.78#
Ankle inversion/ adduction at footstrike (°)	2.04 ± 2.74	-0.16 ± 2.62	0.06	0.85#

* Statistically significant difference for shod, p<0.05; ** Statistically significant difference from shod, p <0.01;
Huge effect size; ## Very large effect size; # Large effect; (-) Value represents ankle eversion/abduction
ES= Effect Size

Spatio-temporal variables

As can be seen in Table 1, contact time(s) was significantly shorter in the barefoot condition (p=0.0001; ES=1.99) compared to the shod condition. Step time(s) was significantly lower in the barefoot condition compared to the shod condition (p=0.01; ES=1.13). Step length (m) was not significantly different between the barefoot and shod conditions (p=0.1; ES=0.65).

Sagittal and frontal plane kinematic variables

Knee flexion was significantly higher in the barefoot condition compared to shod running (p=0.000004; ES=2.61), while ankle dorsi-flexion was significantly higher with running shoes compared to barefoot (p=0.02; ES=1.12) (Table 1). Although no significant differences were found in knee varus/adduction (p=0.08) or ankle inversion/adduction (p=0.06) between shod and barefoot running, a very large practical significant difference was found between the two conditions (knee varus/adduction ES=0.78; ankle inversion/adduction ES=0.85).

DISCUSSION

Differences in spatio-temporal and kinematic and variables were studied to gain a better understanding of changes in the lower limbs at the foot/shoe-ground interface between shod and barefoot running. The fact that significant differences were found between the running conditions in the sagittal plane supports the hypothesis that acute changes would be observed in lower limb kinematics in habitually shod runners not accustomed to barefoot running.

Barefoot running displayed significantly higher step frequencies (9.42 more steps/min), with a trend of shorter step lengths compared to the shod condition. Higher step frequencies during barefoot running have been previously reported in habitually shod (De Wit *et al.*, 2000; Divert *et al.*, 2008; Smith *et al.*, 2010) and habitually barefoot (Squadrone & Gallozzi, 2009) runners. However, reputable barefoot coaches usually recommend a minimum step frequency of 180 steps/min (Sandler & Lee, 2010; Wallack & Saxton, 2011). To achieve this, runners in the present study would have needed to increase their step frequency from shod to barefoot running by approximately 12%, of which only 6% was achieved. Reducing step lengths by 10% was predicted to reduce the probability of attaining tibial stress fractures by 3-6%, despite the corresponding increase in number of load cycles (Edwards *et al.*, 2009). Such large increases in step frequency did not occur naturally in the current participants in the barefoot condition. This suggests that habitually shod runners may require an adaptation or learning period when transitioning to barefoot running in order to completely reduce their step lengths into an acceptable impact-moderating range. Alternatively, coaches may provide verbal instruction to prevent over striding in newly transitioned barefoot runners. Studies which compare natural versus instructed changes in kinematics over a period of several weeks would help clarify whether coaching of “correct barefoot technique” is advisable for runners wishing to add barefoot running in their training regimen.

Time spent contacting with the ground was considerably reduced with the barefoot condition, which is in agreement with previous studies (De Wit & De Clercq, 2000; Squadrone & Gallozzi, 2009; Braunstein *et al.*, 2010). Derrick *et al*. (2004) theorised that the changes in spatio-temporal kinematics to barefoot running are mainly due to changes in touchdown geometry and the consequent joint movements, which occur at foot strike. Certainly, immediate changes at the ankle angle at foot strike in the barefoot condition were observed, with an average of 6.23° more ankle plantar-flexion compared to the shod condition. On visual inspection, most of the runners acutely adapted to run with a midfoot striking pattern while unshod, with the ball of the foot and the heel landing almost simultaneously (Lieberman *et al*., 2010). Ankle plantar-flexion has been found to increase up to 12° at foot strike when running barefoot on hard surfaces compared to running in either low or high cost shoes (Bishop *et al.*, 2006).

The significantly greater ankle plantar-flexion observed during the barefoot condition in this study may have been a function of the lack of shoe heel/midsole height in the absence of a shoe, or as a function of surface hardness. Lieberman *et al*. (2010) stated that the typical rear foot strike pattern, with the ankle landing in the dorsi-flexed position, is a function of the additional heel height of the modern cushioned shoe. Similarly, Robbins and Waked (1997) speculated that shoes with thinner midsoles allow runners to sense the severity of impacts and thus adjust kinematics, while running shoes with a thicker midsole would mask the magnitude or severity of impact shock. While not controlled for, all the participants of this study wore modern running shoes with significant amount of cushioning of at least 20mm in heel height. The authors of the current study acknowledge that heel height may have affected the ankle touchdown kinematics. However, Hamill *et al*. (2011a) showed evidence, which refutes this hypothesis. These authors found that running shoes varying from 2mm to 20mm in heel height did not influence ankle dorsi-flexion angles (11.14±4.46˚) at initial contact or diminish impact force characteristics in a similar sample of participants under similar surface conditions to this study. Conversely, when their participants ran barefoot, their ankles landed in a plantar-flexed position (-7.13±3.00˚). Their study concluded that impact characteristics during running are dependent on the barefoot versus shod condition, and not dependant on the thickness of midsole cushioning. Another study from the same laboratory (Hamill *et al*. 2011b), found that while running barefoot, the majority of habitually shod runners would alter their ankle from a dorsi-flexed (7.55±6.39˚) to a plantar-flexed (-6.97±2.13˚) position as the surface changed from soft (mat) to hard (no mat). These results were believed to occur because their participants either unconsciously anticipated or actually physically experienced pain under the barefoot heel on the hard (no mat) surface and thus attempted to reduce it using altered kinematics. Indeed, some participants in the current study did mention that they experienced discomfort under their heel during the barefoot running condition. The use of a subjective questionnaire regarding individual perceived pain or discomfort under the heel could have been of benefit to this study and is advised for future research on this topic.

It should be noted that despite the significantly more plantar-flexed ankle, the variance (s=4.54°), around the mean between barefoot runners was large. This suggests that there were still some runners who maintained similar dorsi-flexion angles (heel strike pattern) to the shod condition, thus partially confirming hypothesis of this study. This finding was evident in a previous study, yet the frequency of heel striking was significantly higher (83%) (Lieberman *et al*., 2010). It is possible that some habitually shod runners may adapt to running in heeled and cushioned shoes (Reenalda *et al.*, 2011), and may be less efficient in adapting their running style to the barefoot condition (Squadrone & Gallozzi, 2009). The results of the current study show that not all habitually shod runners will make natural anticipatory adjustments in foot strike pattern when running barefoot on hard surfaces. These specific runners may be labelled “non-adaptors” to acute barefoot running and may require the aid of specialised verbal instructions on correct barefoot landing technique. Several proponents of barefoot running state that barefoot running is a learned skill and advocate correct barefoot technique such as "listen to your body", or "avoid landing on your heel" (Sandler & Lee, 2010; Wallack & Saxton, 2011). In a recent survey by Rothschild (2011), 184 (23.4%) out of 785 runners listed "lack of adequate instruction" as one of their highest perceived barriers when attempting transitioning to barefoot running. Yet, a vast number (671; 85.5%) stated that they would be more likely to continue with or attempt barefoot or minimalist shod running if provided with adequate instruction from a professional. Future studies should investigate the effect of verbal instructions related to "correct" barefoot landing technique on both acute and prolonged changes in foot strike kinematics. Results from such studies would help clarify whether or not such verbal instructions are beneficial from an "impact force" or kinetic standpoint.

In the current study, a significantly greater degree of knee flexion at foot strike (7.74°) was found to occur while running barefoot compared to shod, supporting previous literature (Van Woensel & Cavanagh, 1992; De Wit *et al.,* 2000; Lieberman *et al.,* 2010; Hamill *et al*., 2011a). Bishop *et al.* (2006) stated that adopting such landing strategies at the knee might be beneficial to the runner. If all other variables are kept constant, simulation models predict that this increase in knee flexion angle would decrease impact ground reaction force peaks by 526.32N (68N for every 1° increase in knee flexion). This greater knee flexion may have also helped to compensate for a more plantar-flexed ankle position at foot strike (De Wit *et al.,* 2000; Williams III *et al.,* 2000).

Although the differences between barefoot and shod conditions with respect to the frontal plane at both the knee and ankle were not significant, the very large effect size for knee varus/adduction and for ankle inversion/adduction suggests a meaningful difference. These non-significant results may have been due to large inter-individual variation found in the foot-ankle anatomy (De Wit *et al*., 2000). At the ankle joint, shod runners were already landing in an everted position at the time of foot strike. In contrast, in the barefoot condition, runners were landing in a more inverted position at foot strike, supporting previous research (Van Woensel & Cavanagh, 1992; De Wit *et al.,* 2000; Morley *et al.,* 2010). Landing with an inverted foot position has important implications. A recent preliminary study showed that a relative increase (120-667%) in ankle inversion at foot strike in the barefoot condition translated to an increase in impulse (9-92%) of the ankle invertor moment compared to that of the shod condition (Samarawickrame *et al*., 2011). Samarawickrame *et al*. (2011:2) emphasised that this increase in invertor moment may cause new demands on the foot and ankle musculature and tendinous structures, and additionally stated that: "these new demands may lead to beneficial effects such as strengthening of muscles and/or detrimental effects through repetitive overloading of the muscles, tendons and bones". Thus, care should be taken to ensure a gradual transition in running technique when habitually shod runners attempt barefoot running for the first time.

While the use of individual footwear was used to promote a more natural running gait pattern, the authors acknowledge that the individual shoe heel height and –weight, midsole stiffness and age of the running shoe were unaccounted for. These footwear characteristics may have affected the overall running kinematics of the participants in the shod condition. Future research on barefoot running should implement a transition period over several weeks to determine if barefoot running would lead to more prominent and permanent changes in running kinematics. Moreover, no studies to date have looked at the effect of various verbal instructions suggested by barefoot coaches, on shod runners who are not able to adapt naturally to “correct” barefoot running kinematics.

CONCLUSION

The current study has provided preliminary evidence to suggest that changes in the foot/shoe-ground interface led to acute changes in selected lower limb kinematic and spatio-temporal variables at footstrike. When running in the barefoot condition, participants generally landed with greater knee flexion, possibly causing more ankle plantar-flexion with a midfoot strike placement. Participants had decreased contact times, as well as an increased step frequency when running in the barefoot condition compared to shod running. However, some runners did not adapt their kinematics, which suggests that a level of skill may be involved when transitioning to the barefoot condition. Running coaches are thus advised to educate those wanting to transition to barefoot running that correct barefoot running kinematics may not come naturally and may require a skill component. Certain verbal cues could be of value for these “non-adaptors”.

Acknowledgement

The authors would like to express their appreciation to the participants and would also like to thank the Department of Sport Science and the Department of Physiotherapy, Stellenbosch University for their support.

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(Subject Editor: Dr. Marlene Schoeman)