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Biomechanical characteristics of barefoot footstrike modalities

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ABSTRACT

Barefoot running has increased in popularity over recent years, with suggested injury risk and performance benefits. However, despite many anecdotal descriptions of barefoot running styles, there is insufficient evidence regarding the specific characteristics of barefoot running. The present study provided reference data for four footstrike modalities adopted across a large cohort of habitually shod male runners while running barefoot: heel strikers (HS), midfoot strikers (MS), forefoot strikers (FS) and a newly defined group, toe runners (TR – contact made only with the forefoot), compared with the three modalities previously reported. Plantar pressure analysis was used for the classification of footstrike modality, with clearly distinguishable pressure patterns for different modalities. In the present study, the distribution of footstrike types was similar to that previously observed in shod populations. The absence of differences in ground contact time and stride length suggest that potential performance benefits of a non-HS style are more likely to be a function of the act of running barefoot, rather than of footstrike type. Kinematic data for the knee and ankle indicate that FS and TR require a stiffer leg than HS or MS, while ankle moment and plantar pressure data suggest that a TR style may put greater strain on the plantar-flexors, Achilles tendon and metatarsal heads. TR style should therefore only be adopted with caution by recreational runners. These findings indicate the importance of considering footstrike modality in research investigating barefoot running, and support the use of four footstrike modalities to categorise running styles.

1. Introduction

Running barefoot or with minimalist footwear has become a popular topic of discussion, fuelled by suggestions of both reduced injury-risk and performance improvements. The proposed benefits are suggested to occur as a result of an altered foot strike pattern, with the forefoot reported to initially strike the ground in habitual barefoot runners, compared with the heel in the majority of shod runners (Lieberman et al., 2010). Lieberman et al. (2010) noted the absence of a distinct 'peak impact force' in forefoot strikers, linking this with a reduced injury risk, a mechanism which was also cited in recent research suggesting lower risk of specific injury in forefoot strikers compared to heel strikers (Daoud et al., 2012). Additionally, aspects of the 'barefoot running style' including lower ground contact time, shorter stride length (Squadrone and Gallozzi, 2009) and the removal of shoe mass (Franz et al., 2012) have been linked to improved running economy. However, there is currently insufficient evidence to support claims of a positive effect of barefoot running on injury risk or performance (Jenkins and Cauthon, 2011; Lorenz and Pontillo, 2012). Evidence is inconclusive with regards to whether barefoot running causes a change in running style to forefoot strike, and if so, how the biomechanics of this running style differ from heel-strike running. Understanding is further clouded because comparisons of footstrike modalities have largely been made between shod and barefoot running, and not within different barefoot footstrike patterns. As a result, it remains unclear whether any benefits or disadvantages of barefoot running may occur as a function of being shoeless, or specifically as a function of footstrike modality.

Footstrike modalities are generally categorised as either rearfoot/heel (HS), midfoot (MS) or forefoot (FS) strikes. However, during an ongoing large-scale prospective study involving barefoot running (Ministry of Defence Research Ethics Committee protocol 090/Gen/09), it has become evident that two distinct modalities of forefoot striking running style are displayed when running barefoot: the forefoot strike, which involves runners striking the ground with their forefoot, before bringing the rest of their foot into contact with the ground; and the 'toe runner' (TR) style, which involves contact being made with the forefoot only during ground contact. Whilst these methods both involve initial ground contact with the forefoot, the biomechanical characteristics of the footstrike differ to result in a differing running style. Although the TR style was described by Lieberman (2012), it has not received attention in the literature, and

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no distinction between the biomechanics of forefoot strike types has been previously made. If footstrike modality is important in determining the effectiveness of barefoot running, such distinctions are necessary.

Lieberman et al. (2010) reported that habitually shod runners predominantly maintained a HS pattern when running barefoot but struck the ground with a flatter foot. Hamill et al. (2011) however reported that all their study participants moved from a HS to a distinct MS when shoes were removed. The equivocal reporting of the behaviour of habitually shod runners when asked to run barefoot is confounded by studies of small sample size, and the use of different surfaces and running velocities, as well as different methods for determination of footstrike modality. Thus, further evidence is required to provide reference data on barefoot running footstrike characteristics. There are also no data comparing MS, FS and TR modalities. The present paper provides a detailed analysis of lower limb angles for different footstrike modalities in a large sample size.

From a performance perspective, the variables of step length and ground contact time have been of interest, with shorter values for both being observed in barefoot conditions compared with shod (Squadrone and Gallozzi, 2009). Thus, in addition to quantifying differences in lower limb kinematics for different footstrike modalities, it would be beneficial to investigate any differences in these variables. With regards to injury risk, it has been suggested that the demand on the calf musculature (gastrocnemius and soleus) and the Achilles tendon is increased for a forefoot strike running style (FS or TR) (Perl et al., 2012). An estimation of the demand placed on the muscle–tendon complex can be provided through the calculation of the sagittal plane moment acting about the ankle joint during stance (e.g. Bobbert et al., 1986). In the present study, this allows investigation of whether the demand on the triceps-surae muscle–tendon complex differs for different footstrike modalities.

No attention has previously been given to the potential implications of a MS, FS or TR style on loading at the metatarsal heads, which are likely to be subjected to greater load for these footstrike modalities. This is despite evidence suggesting that increased metatarsal loading may increase the risk of metatarsal stress fractures (Arndt et al., 2003; Nagel et al., 2008; Nunns et al., 2012). Measurement of plantar pressure during barefoot running in the current study allows a comparison of the magnitude and timing of peak pressures and impulse at specific regions of the foot.

The aim of this study is to provide reference data for four types of footstrike modality amongst habitually shod fit young males undertaking barefoot running, and to investigate whether footstrike modality influences variables associated with performance and injury risk. Specifically, it is hypothesised that: (a) FS and TR would display a shorter step length and ground contact time than HS and MS; (b) FS and TR would exhibit greater ankle moments than HS and MS; and (c) peak pressures and impulse would be greater beneath the metatarsal heads in FS and TR than for HS and MS.

2. Methods

As part of a larger prospective injury study, 1065 Royal Marine (RM) recruits were assessed in the second week of a 32-week progressive training programme over a two-year period between 2010 and 2012, with 120 included in the present study. Ethical approval for the study was granted by the Ministry of Defence Research Ethics Committee. All participants were free from injury at the time of assessment and provided informed consent. Body mass was obtained in shorts and t-shirt to the nearest .1 kg (Sartorius AG, Goettingen, Germany) and height was measured to the nearest .1 cm using a stadiometer (Seca 202, Seca, Hamburg, Germany).

Active markers were placed at the following sites: greater trochanter; lateral and medial epicondyle; midline of the posterior shank, below the gastrocnemius muscle belly; lateral malleolus; two markers defining the vertical line of the posterior calcaneous; articulation of the medial cuneiform and proximal end of the third metatarsal; lateral articulation of the fifth metatarsophalangeal joint. Participants ran over a 2 m pressure plate (RSScan International, Belgium, 2 m × .4 m × .02 m, with 16,384 resistive sensors, 200 Hz, 10 sensors/4 cm^2) set within an EVA runway (.02 m thick, hardness rating of 65 Shore A) with a total carpeted length of 15 m with approximately 3 m before and 2 m after the pressure plate and EVA runway. Synchronised bilateral 3D kinematic data were obtained at 200 Hz using two aligned Coda mpx30 units (Charnwood Dynamics Ltd., Leicestershire, UK).

Table 1
Description of footstrike classifications used in the study.

Category	Description
HS (heel strikers)	Only heel contact made in the first two frames of stance.
MS (midfoot strikers)	Initial contact made with the midfoot region of the foot, or several regions within the first two frames of contact.
FS (forefoot strikers)	Initial contact with the forefoot before making contact with the rest of the foot (after at least two frames following contact).
TR (toe runners)	Contact made only with forefoot during stance.
Mixed	Demonstrate more than one footstrike type either between or within feet.

Participants were given sufficient warm-up trials in order to become accustomed to the testing environment. These continued until the participant was comfortable with the barefoot protocol, and able to consistently replicate a consistent stride at the required speed. An assessor observed the runner to ensure that a consistent footstrike pattern was adopted. If this was not the case, the participant was given more time to practice, or deemed to have a 'mixed' footstrike pattern if no improvement was made. Following habituation, five successful barefoot running trials were performed at 3.6 m.s^{-1} ($\pm$5%) for each of 1065 RM recruits. Running speed was monitored using hip-height photocells placed 2 m apart either side of the pressure plate. A trial was deemed successful if both feet contacted the 2 m plate, the test velocity was achieved, and all Coda markers were successfully detected.

Plantar pressure profiles were inspected to determine the footstrike modality of each recruit. The plantar surface of the foot was divided into three (rearfoot, midfoot and forefoot sections), and inspected during the first two frames of ground contact. Five categories of running style were identified and are described in Table 1.

Fig. 1 presents typical plantar pressure images for the four footstrike categories identified. The number of participants classified into each category of footstrike modality is detailed in Table 2.

Those participants presenting a mixed running style were eliminated from the analysis. *A-priori* analysis based on data from previous research (Nunns et al., 2012) indicated that large effect sizes could be expected (peak pressure at MT3, Cohen's d=3.4; peak dorsiflexion, Cohen's d=1.4), and that a power level of .9 could be achieved with a sample size of 24 participants in each group. Given the availability of greater numbers, one foot was randomly selected for analysis from 30 individuals in each of the four foot strike categories.

3D knee, ankle and rearfoot kinematics were calculated using a customised Matlab code (The Mathworks, US), providing angle at touchdown, peak angle (peak knee flexion, ankle dorsiflexion and rearfoot eversion), range of motion from touchdown to peak, time of peak angle as a percentage of stance and average rate of flexion/dorsiflexion/eversion respectively. Two-dimensional foot angle relative to the ground at touchdown was calculated using a line from the inferior calcaneous marker to the fifth metatarsophalangeal joint marker. Fig. 2 illustrates the angle conventions adopted. Step length was calculated as the distance between the inferior calcaneous marker of each foot for consecutive ground contacts, and presented as a percentage of height.

Peak pressure and impulse were recorded for each trial at locations defined by the placement of masks within the *Footscan* software (Fig. 3). The peak active force was also identified and normalised to body weight.

The moment arm of the ground reaction force vector about the ankle joint was calculated as the horizontal distance between the ankle joint centre and the pressure plate centre of force. This distance was multiplied by the vertical force to provide a time history of the simplified ankle moment, from which the maximum value was identified and used to represent peak plantar-flexion moment, normalised to bodyweight. The timing of this peak moment, as a percentage of stance, was also reported.

For each variable, the mean of five trials for each of the 120 participants included was calculated. Differences between footstrike modalities were then evaluated by one-way ANOVA, with post hoc Tukey tests (PASW Statistics version 18.0.0, SPSS Inc., Chicago, IL, USA). Effect sizes were calculated for significantly different pairs of footstrike modalities using Cohen's d (Cohen, 1988).

3. Results

Descriptive characteristics for each footstrike group are presented in Table 3. The only characteristic that differentiated the