Gait & Posture 41 (2015) 825–829

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length Article

Dynamic in-vivo assessment of navicular drop while running in barefoot, minimalist, and motion control footwear conditions

Scott E. Hoffman [a], Cathryn D. Peltz [a,*], Jeffrey A. Haladik [a], George Divine [b], Matthew A. Nurse [c], Michael J. Bey [a]

[a] Henry Ford Health Systems, Department of Orthopaedic Surgery, Bone and Joint Center, 2799W. Grand Blvd., E&R 2015, Detroit, MI 48202, United States
[b] Henry Ford Health Systems, Department of Public Health Science, 2799W. Grand Blvd., Detroit, MI 48202, United States
[c] Nike, Inc., Nike Sport Research Lab, Beaverton, OR, United States

ARTICLE INFO

Article history:
Received 15 September 2014
Received in revised form 12 December 2014
Accepted 28 February 2015

Keywords:
Navicular drop
Pronation
Barefoot running
Minimalist shoe
Dynamic X-ray
Foot posture

ABSTRACT

Running-related injuries are common and previous research has suggested that the magnitude and/or rate of pronation may contribute to the development of these injuries. Accurately and directly measuring pronation can be challenging, and therefore previous research has often relied on navicular drop (under both static and dynamic conditions) as an indirect assessment of pronation. The objectives of this study were to use dynamic, biplane X-ray imaging to assess the effects of three footwear conditions (barefoot, minimalist shoes, motion control shoes) on the magnitude and rate of navicular drop during running, and to determine the association between static and dynamic measures of navicular drop. Twelve healthy distance runners participated in this study. The magnitude and rate of navicular drop were determined by tracking the 3D position of the navicular from biplane radiographic images acquired at 60 Hz during the stance phase of overground running. Static assessments of navicular drop and foot posture were also recorded in each subject. Footwear condition was not found to have a significant effect on the magnitude of navicular drop ($p = 0.22$), but motion control shoes had a slower navicular drop rate than running barefoot ($p = 0.05$) or in minimalist shoes ($p = 0.05$). In an exploratory analysis, static assessments of navicular drop and foot posture were found to be poor predictors of dynamic navicular drop in all footwear conditions ($p > 0.18$).

1. Introduction

Running is an important part of many peoples' efforts to maintain an active, healthy lifestyle, but running-related injuries are common. Running-related injuries such as medial tibial stress syndrome ("shin splints"), patellofemoral pain syndrome ("runner's knee"), Achilles tendonitis, plantar fasciitis, and iliotibial band syndrome have been reported to affect approximately 20–79% of runners on an annual basis [1,2]. Unfortunately, the etiology of running-related injuries is not well understood. Previous research has reported that increasing age, female gender, previous injury, high BMI, low fitness level, foot posture, and excessive training distance are associated with injury [1–3]. Previous research has also suggested that pronation or pronation rate may be associated with injury [4,5], and this belief has led to the development of running shoes aimed at reducing pronation (e.g., motion control shoes). However, the effects of footwear on pronation are not fully understood.

One reason why the effects of footwear on pronation are not fully understood is because accurately measuring pronation – which involves a complex interaction of eversion, dorsiflexion, and abduction – is difficult. Pronation has typically been assessed using static measures of foot posture (e.g., [6]), direct measurements of rearfoot motion (e.g., [7]), and through measures of navicular drop (ND) (e.g., [8]). Each approach has contributed significantly to the understanding of foot/ankle function, but none of these approaches is without limitations. For example, a significant limitation of static measures of foot posture is that they may not accurately predict pronation under dynamic conditions [9–11]. Optical motion capture systems are capable of providing dynamic assessments of rearfoot motion, but techniques that rely on surface markers often have limited (or unknown) in-vivo accuracy and are not well suited for

---

[*] Corresponding author. Tel.: +1 313 916 8680; fax: +1 313 916 8812.
E-mail address: cpeltz1@hfhs.org (C.D. Peltz).

http://dx.doi.org/10.1016/j.gaitpost.2015.02.017
0966-6362/© 2015 Elsevier B.V. All rights reserved.

quantifying certain joint rotations that are involved in pronation (e.g., subtalar joint, talonavicular joint). An alternative approach for assessing pronation is to quantify ND, i.e., the change in vertical position of the navicular tuberosity. The original description of this technique involved measuring ND with a ruler [12], but since then ND has been measured using a coordinate measuring machine [13], optical motion capture systems (e.g., [14]), single-plane fluoroscopy [15], and a wearable in-shoe sensor [16]. Similar to measures of rearfoot motion, ND has often been quantified using skin- or shoe-mounted markers that are susceptible to errors due to marker motion relative to the underlying bone. For example, Shultz and colleagues used single-plane fluoroscopy to report that soft-tissue artifact associated with skin-mounted markers at the navicular ranged from 7.6 mm at heelstrike to 16.7 mm at toe-off [17]. Another limitation is that ND is often measured under static conditions, and previous research has shown that static measures of ND have poor association with dynamic measures [9–11]. Similarly, ND is often measured while barefoot, but the extent to which ND measured in barefoot conditions accurately predicts ND in shod conditions is not known.

The primary objective of this study was to use biplane X-ray imaging and model-based tracking – a radiographic approach that offers higher in-vivo accuracy than conventional motion capture techniques – to assess the effects of three footwear conditions on the magnitude and rate of ND during running. Secondary objectives of this study were to assess: (1) the association between static and dynamic measures of ND, (2) the association between barefoot and shod measures of ND, and (3) the association between static foot posture and ND. Previous research with optical motion capture techniques have shown that footwear can affect rearfoot-based measures of pronation (e.g., [7]), and therefore we hypothesized that footwear would have a significant effect on ND and ND rate. Based on the findings from previous studies [9–11], we also hypothesized that static ND would be a poor predictor of dynamic ND, and that barefoot ND would be a poor predictor of shod ND.

2. Methods

After Institutional Review Board approval and informed consent were obtained, a convenience sample of 12 subjects (six female/male, age: 24.2 ± 4.4) enrolled in the study. Subjects were required to have run at least 25 miles per week and have been injury free for the year prior to testing. Subjects were excluded from participating in the study if they had previously had any lower extremity surgery. All subjects were recruited via word of mouth.

Testing began with static assessments of foot posture and ND. Briefly, one observer (SEH) assessed foot posture using the Foot Posture Index (FPI) where scores of −12 to −6 were considered highly supinated, −5 to −1 considered supinated, 0 to 5 considered normal, 6 to 9 considered pronated, and >10 considered highly pronated [6]. To assess palpated ND, the same observer marked each subject's navicular tuberosity with an ink pen, and then used a ruler to measure the difference in vertical position of the navicular tuberosity between seated and standing (i.e., a modified Brody approach) [12]. This process has also been referred to as an assessment of functional static ND, as opposed to subtalar static ND which records the difference in navicular height with the foot in a subtalar neutral position and the foot in a relaxed calcaneal position during bilateral weight bearing [9]. This process was performed three times in order to establish an average palpated ND for each subject.

Dynamic radiographic images of each subject's left foot were acquired during the stance phase of overground running with a custom biplane X-ray system [18]. Following 15 min of treadmill jogging, radiographic images were acquired of the subject's left foot at 120 Hz as subjects ran at a self-selected pace along a 50 foot long elevated runway. Images were acquired as subjects ran in three footwear conditions: a minimalist shoe (Nike Free 3.0 V4), a motion control shoe (Nike Zoom Structure Triax 15+), and barefoot. Three trials (i.e., three stance phases) were collected in each footwear condition and the testing order was balanced so that two subjects (one male, one female) were tested in each of the six combinations of footwear testing order.

Following laboratory testing, a computed tomography (CT) scan was acquired of each subject's left foot and ankle. From the CT scan, the navicular was segmented from surrounding tissues and reconstructed into a 3D bone model using commercial software (Mimics 14.1, Materialise, Ann Arbor, MI). Using custom software, an anatomical landmark was identified on the CT-based navicular bone model at the navicular tuberosity. This was accomplished by rotating in 3D the bone model, identifying the medial most aspect of the navicular, and then placing an anatomical landmark on this medial most aspect. The location of this anatomical landmark was then verified by observing its position on the navicular from superior/inferior, medial/lateral, and anterior/posterior views.

After correcting the images for distortion and performing a 3D calibration as previously described [18,19], custom software was used to track the 3D position of the navicular from the biplane X-ray images [18]. This process has been shown to have an accuracy of between 0.4 and 0.9 mm in the glenohumeral joint, tibiofemoral joint, patellofemoral joint, and cervical spine [18,20–22]. The 3D position and orientation of the navicular was expressed in a laboratory-based coordinate system whose axes were aligned in the superior/inferior, medial/lateral, and anterior/posterior directions relative to the direction of running. In order to assess radiographic ND, the superior/inferior position of the navicular tuberosity landmark was recorded for each frame of data. Radiographic ND was defined as the change in the superior/inferior position of the navicular tuberosity from the start of flat foot contact to maximum pronation. In order to account for differences in footstrike patterns, the start of flat foot contact was identified as the first frame at which the heel and forefoot were in contact with the testing platform prior to the onset of weight bearing. The onset of weight bearing was identified on the radiographic images by deformation of the heel or forefoot, elongation of the arch, or reduction of joint space between the talus and calcaneus. Maximum pronation was identified as the frame associated with the lowest superior/inferior position of the navicular tuberosity. Radiographic ND was measured for each trial and then these data were averaged over three trials to produce an average radiographic ND for each subject and footwear condition. ND time was recorded as the time from foot contact to maximum pronation, and radiographic ND rate was calculated from the measures of radiographic ND and ND time.

All data were assessed and verified for normality using the Kolmogorov–Smirnov test. The effects of footwear condition (barefoot, minimalist, motion control) on radiographic ND, ND time, and radiographic ND rate were assessed with a repeated measures ANOVA. If the ANOVA was significant, Bonferroni post-hoc tests corrected for multiple comparisons were then calculated in order to compare between each pair of footwear conditions. Linear regression was used to assess the association between palpated ND and radiographic ND, and to assess the association between barefoot and shod measures of radiographic ND. Statistically significant differences were set a priori at $p < 0.05$.

3. Results

No difference was detected in the magnitude of radiographic ND ($p = 0.22$, Fig. 1A). Specifically, radiographic ND was nearly identical in the barefoot (6.7 mm (95% confidence interval (CI):