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

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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

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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):

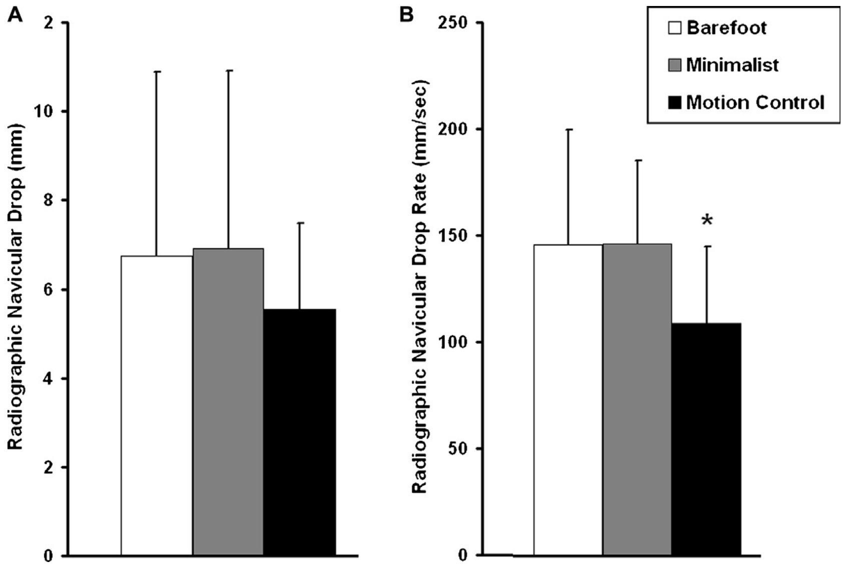

Fig. 1. Footwear condition was not found to have a significant effect on radiographic navicular drop (A, $p = 0.22$), but it did have a significant effect on radiographic navicular drop rate (B, $p = 0.03$). *Significantly less than both the barefoot and minimalist footwear conditions ($p = 0.05$). The error bars represent 1 standard deviation.

4.4–9.0 mm), range: 2.3–15.3 mm) and minimalist (6.8 mm (95% CI: 4.6–8.9 mm), range: 1.8–15.5 mm) conditions, but lower in the motion control condition (5.5 mm (95% CI: 4.4–6.6 mm), range: 3.6–9.3 mm). One third of the runners utilized in this experiment produced their largest radiographic ND in each footwear condition. Specifically, the greatest radiographic ND occurred in the barefoot condition for four subjects (3 males, 1 female), in the minimalist footwear condition for four subjects (1 male, 3 females), and in the motion control footwear condition for four subjects (2 males, 2 females).

Footwear condition had a statistically significant effect on the radiographic ND rate ($p = 0.03$, Fig. 1B). Specifically, the motion control footwear condition (109 mm/s (95% CI: 89–129 mm/s), range: 66–179 mm/s) was significantly less than both the barefoot (146 mm/s (95% CI: 124–168 mm/s), range: 94–203 mm/s, $p = 0.05$) and minimalist (146 mm/s (95% CI: 115–177 mm/s), range: 81–275 mm/s, $p = 0.05$) footwear conditions. No significant difference was detected between the barefoot and minimalist footwear conditions ($p = 0.99$). The average ND time was 52 ms (95% CI: 24–80 ms, range: 33–83 ms) in the motion control shoes, 47 ms (95% CI: 22–72 ms, range: 17–75 ms) in the minimalist shoes, and 46 ms (95% CI: 22–70 ms, range: 17–92 ms) in the barefoot condition ($p = 0.71$).

Measures of palpated ND were not found to be significantly associated with radiographic ND in the barefoot ($p = 0.73$, $R^2 = 0.01$), minimalist ($p = 0.33$, $R^2 = 0.09$), or motion control ($p = 0.30$, $R^2 = 0.11$) footwear conditions (Fig. 2). Similarly, FPI scores were not found to be significantly associated with radiographic ND in the barefoot ($p = 0.92$, $R^2 = 0.001$), minimalist ($p = 0.31$, $R^2 = 0.11$), or motion control ($p = 0.18$, $R^2 = 0.17$) footwear conditions (Fig. 3).

Radiographic ND in the barefoot condition was not significantly associated with the minimalist footwear condition ($p = 0.13$, $R^2 = 0.24$) or the motion control footwear condition ($p = 0.89$, $R^2 = 0.003$, Fig. 4).

4. Discussion

The primary objective of this study was to assess the effects of three footwear conditions on the magnitude and rate of radiographic ND during running. The study indicated that running in motion control shoes resulted in a lower radiographic ND rate than both barefoot and minimalist footwear conditions (Fig. 1B), but that no difference was detected between footwear conditions in the magnitude of radiographic ND (Fig. 1A). The study also found that radiographic ND in the minimalist footwear condition was significantly associated with the barefoot condition (Fig. 4). However, the study failed to detect significant associations between radiographic ND and either palpated ND (Fig. 2) or FPI scores (Fig. 3).

Further analysis of the radiographic ND data indicate that there was, on average, a 4.5 ± 2.6 mm (range: 1.1–9.4 mm) difference between the maximum and minimum radiographic ND values across the 12 subjects. Although this certainly indicates that footwear had an appreciable effect on radiographic ND on individual subjects, the effects of footwear on radiographic ND were inconsistent across subjects (Table 1). Specifically, maximum radiographic ND was evenly distributed across the footwear conditions (i.e., 4 subjects each had their maximum radiographic ND in the barefoot, minimalist, and motion control conditions). However, the minimum radiographic ND occurred most often in the motion control shoes (6/12 subjects),

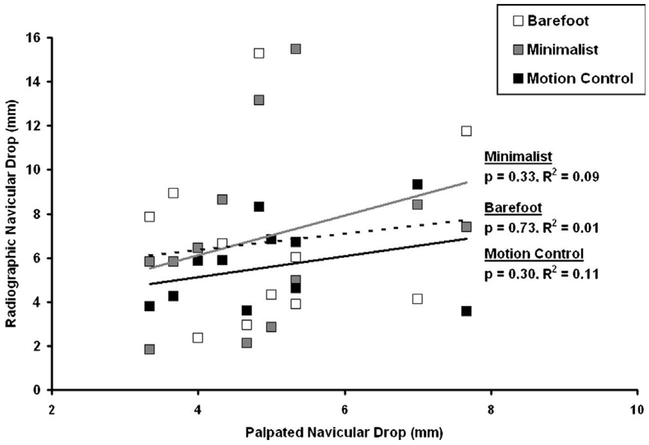

Fig. 2. Palpated navicular drop (determined using a modified Brody method [12]) was not found to be significantly associated with radiographic navicular drop in the barefoot ($p = 0.73$), minimalist ($p = 0.33$), or motion control ($p = 0.30$) footwear conditions.

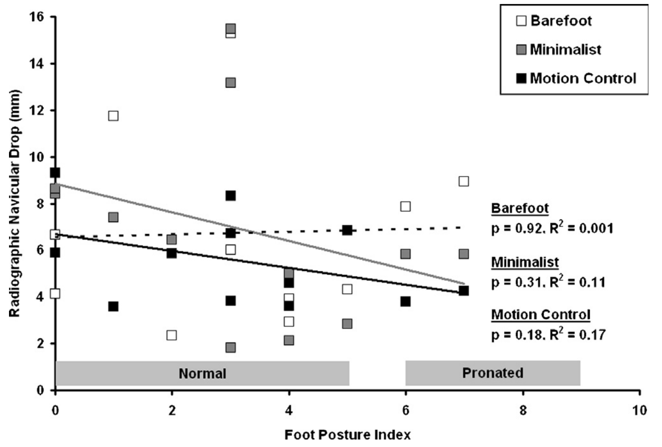

Fig. 3. Foot posture index scores were not found to be significantly associated with radiographic navicular drop in the barefoot ($p = 0.92$), minimalist ($p = 0.31$), or motion control ($p = 0.18$) footwear conditions.

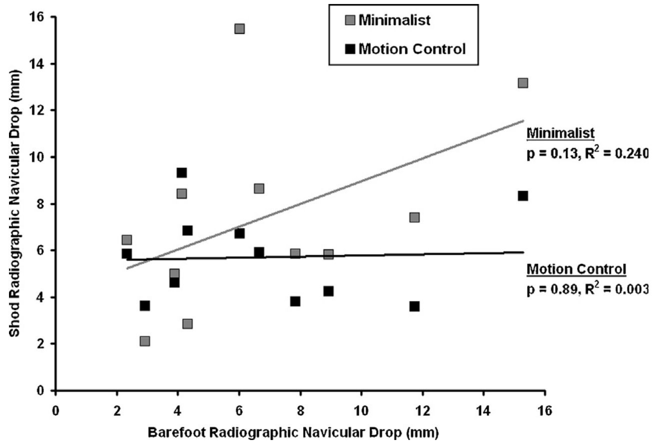

Fig. 4. Radiographic navicular drop in the barefoot condition was not significantly associated with the minimalist footwear condition ($p = 0.13$) or the motion control footwear condition ($p = 0.89$).

followed by an even distribution between the barefoot (3/12 subjects) and minimalist (3/12 subjects) footwear conditions. While the implications of these data is not clear, previous research (e.g., [23–25]) suggests that one potential explanation is that subject-specific interaction between foot morphology and shoe fit may have influenced the radiographic ND data. Collecting radiographic ND data from the subjects in their native running shoes may have provided insight into the extent to which ND is influenced by footwear and/or subject-specific factors, but it is a limitation that this study failed to acquire those data. At a minimum, it appears that the interaction between radiographic ND and the footwear conditions assessed here is subject-specific and not adequately captured by any of the outcome measures recorded in this study.

The statistically significant differences in radiographic ND rate (Fig. 1B) appear to be the result of subtle differences in both the magnitude and duration of radiographic ND between the three footwear conditions. Although differences in radiographic ND were not found to be statistically significant ($p = 0.22$, Fig. 1A), the average magnitude of radiographic ND in the motion control shoes was 1.2 mm lower than the barefoot condition and 1.3 mm lower than the minimalist footwear condition. In addition, the ND time in the motion control shoes (52 ± 50 ms) was 5–6 ms longer than in the barefoot (46 ± 43 ms) and minimalist (47 ± 44 ms) conditions, although these differences were not statistically significant ($p = 0.71$). Although the magnitude of these differences in radiographic ND and radiographic ND time are small and not statistically significant, the combined effect results in a relative difference in radiographic ND rate of 34% between footwear conditions (Fig. 1B).

Previous research has yielded conflicting findings regarding the extent to which static ND, assessed using the method described by Brody [12], accurately predicts dynamic ND. For example, previous studies have shown that static ND is significantly associated with dynamic ND, hallux pressure, and forefoot pressure [14,26]. However, Rathleff and colleagues acknowledged that static ND could not be used as a subject-specific predictor of dynamic ND [14], while Jonely and colleagues reported that the strength of the associations between ND and foot pressures were only poor to fair [26]. The current study suggests that the specific approach used in this study for assessing palpated ND may not be a strong predictor of radiographic ND (Fig. 2). This lack of association is likely due in large part to actual differences in ND between static and dynamic conditions, but may also be affected by the accuracy of the measurement techniques. The experimental approach used in this study has consistently demonstrated sub-millimeter accuracy for measuring dynamic, in-vivo joint motion [18,20–22]. The Brody technique for assessing static ND has been shown to have high reliability [27], but the in-vivo accuracy has not, to our knowledge, been reported. Furthermore, it is plausible that the specific approach used in this study for assessing static ND (i.e., functional static ND versus subtalar static ND) may have affected the predictive value of these relationships. Lastly, it was impossible to verify if the baseline flatfoot position used when assessing static

Table 1
Individual and overall data for the 12 subjects tested in this study. The individual values are reported as the mean (st. dev.) of three trials. Static navicular drop was assessed using the method described by Brody [19]. FPI = foot posture index, BF = barefoot, MIN = minimalist shoe, MC = motion control shoe.

Subject	Gender	Age	Current shoe	FPI	Navicular drop (mm)				Navicular drop rate (mm/s)		
					Static	BF	MIN	MC	BF	MIN	MC
1	M	23	Brooks Defyance	3	4.8 (1.6)	15.3 (4.2)	13.2 (1.2)	8.3 (2.5)	167 (34)	186 (29)	134 (15)
2	M	25	Saucony Mirage II	1	7.7 (1.2)	11.7 (1.1)	7.4 (2.6)	3.6 (0.8)	203 (20)	151 (41)	82 (25)
3	M	30	Saucony Mirage II	5	5.0 (1.0)	4.3 (2.0)	2.8 (1.0)	6.9 (2.5)	194 (105)	206 (21)	91 (36)
4	M	26	Brooks Glycerin	0	7.0 (1.7)	4.1 (1.6)	8.4 (1.1)	9.3 (1.7)	108 (26)	134 (5)	154 (29)
5	M	26	Asics Fluent	6	3.3 (1.2)	7.9 (2.5)	5.8 (1.3)	3.8 (1.6)	128 (182)	116 (7)	81 (46)
6	M	22	Nike Structure Triax	3	5.3 (0.6)	6.0 (1.6)	15.5 (3.0)	6.7 (3.2)	145 (27)	275 (59)	179 (36)
7	F	26	Mizuno Wave Inspire 8	4	5.3 (0.6)	3.9 (4.5)	5.0 (1.4)	4.6 (0.6)	164 (43)	132 (46)	66 (22)
8	F	21	Asics Gel Blur 33	4	4.7 (1.5)	2.9 (1.3)	2.1 (0.5)	3.6 (1.0)	115 (15)	106 (73)	100 (28)
9	F	21	New Balance Barringer	7	3.7 (0.6)	8.9 (1.6)	5.8 (1.1)	4.2 (0.9)	101 (21)	81 (7)	69 (15)
10	F	33	Nike Free	0	4.3 (1.5)	6.7 (0.9)	8.6 (1.1)	5.9 (1.4)	186 (28)	148 (10)	133 (33)
11	F	18	Saucony Guide 5	3	3.3 (1.2)	–	1.8 (1.3)	3.8 (1.3)	–	95 (84)	85 (52)
12	F	19	New Balance Minimus	2	4.0 (1.0)	2.3 (1.1)	6.4 (1.7)	5.9 (1.2)	94 (36)	123 (20)	132 (22)
Overall	–	24.2 (4.4)	–	3.2 (2.2)	4.9 (1.4)	6.7 (4.0)	6.9 (4.1)	5.5 (1.9)	146 (39)	146 (54)	109 (36)

ND was identical to the flatfoot position identified from the dynamic trials, and therefore subtle differences in foot position and/or load distribution may have influenced the associations between the static and dynamic measures of ND.

This study also failed to detect a significant association between radiographic ND and FPI scores (Fig. 3). Nielsen and colleagues reported a statistically significant association between ND and FPI scores in 280 subjects, with ND increasing with a more pronated foot posture [28]. However, this association was weak, with FPI explaining only 13% of the variation in ND. Consequently, perhaps it was not surprising that the study failed to detect a statistically significant association between these outcome measures in this small sample size of 12 subjects. Furthermore, the lack of significant findings in the current study may have been influenced by the relatively narrow range of FPI scores in the tested subject population. The FPI scale ranges from −12 to 12, but the FPI scores in the subjects tested ranged from only 0 to 7 (Table 1). It is possible that testing additional subjects over a wider range of FPI scores may have revealed a stronger association between FPI score and radiographic ND.

There are several limitations with this study. First, the subjects had limited time to adapt to the different footwear conditions. Thus, the findings reported here may be indicative of only the initial adaptation period and it is plausible that the findings may be different after extended use. Another limitation of this study is that subjects were allowed to run at a self-selected speed and running speed was not directly measured. Although this study defined maximum pronation as the lowest superior/inferior position of the navicular tuberosity, it is certainly plausible that the rearfoot may have continued to pronate or that there was medial drift of the navicular without any further lowering. Finally, this study utilized a relatively small and homogeneous sample of runners and only three trials were collected per footwear condition because of radiation exposure considerations. A post hoc power analysis suggests that approximately 250 subjects would have been required to detect a statistically significant difference in radiographic ND ($\alpha = 0.05$, $\beta = 0.2$). Furthermore, the study was not powered to look at the associations between palpated and radiographic measures of ND, barefoot and shod measures of radiographic ND, or FPI scores and radiographic ND (i.e., the secondary objectives of the study). Consequently, these associations are presented only as exploratory analyses and the results should be interpreted with care. Therefore, it is unclear to what extent the results of this study can be generalized to a larger population of runners.

In summary, this study indicates that footwear condition was not found to have a significant effect on the magnitude of radiographic ND, but that running in motion control shoes results in a slower radiographic ND rate than running barefoot or in minimalist shoes. Furthermore, palpated ND and foot posture were found to be poor predictors of radiographic ND in all footwear conditions. In addition, there was a significant association between measures of radiographic ND under barefoot and minimalist conditions, though this was not a particularly strong relationship.

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Conflict of interest

The following authors have no conflict of interest: Scott E. Hoffman, Cathryn D. Peltz and Jeffrey A. Haladik. Matthew A. Nurse is a paid employee of the study sponsor (Nike). Michael J. Bey received funding from Nike for this study.

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