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Jennifer L. Bishop [a], Matthew A. Nurse [a] & Michael J. Bey [b]

[a] Nike, Inc., NSRL, One Bowerman Drive, Beaverton, 97005, United States

[b] Henry Ford Health System, Bone and Joint Center, Detroit, United States

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Jennifer L. Bishop[a]*, Matthew A. Nurse[a] and Michael J. Bey[b]

[a]*Nike, Inc., NSRL, One Bowerman Drive, Beaverton, 97005 United States;* [b]*Henry Ford Health System, Bone and Joint Center, Detroit, United States*

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Ankle strains and sprains are one of the most common basketball injuries. These injuries are often the result of excessive ankle inversion. High-top shoes are worn because it is thought that they limit inversion and, therefore, reduce the risk of inversion injuries. However, it is difficult to quantify inversion of the ankle inside the shoe with traditional measurement techniques, making comparison between footwear conditions difficult. The purpose of this study was to compare inversion of the ankle and shoe in a high-top and a low-top shoe during aggressive lateral cutting. It was hypothesised that ankle inversion would be lower than shoe inversion in both a high-top shoe and a low-top shoe. Six male basketball players were analysed over three dynamic cutting trials in each condition. As hypothesised, shoe inversion during aggressive cutting was higher than ankle inversion in the high-top shoe (17°) and the low-top shoe (25.5°). Future research should focus on determining the relative contribution of ankle inversion inside the shoe versus relative motion between the shoe and the body to ankle injuries.

Keywords: lateral motion; kinematics; ankle; high top; athletic footwear; x-ray imaging; in vivo

1. Introduction

Various modifications have been made to footwear in an attempt to reduce ankle inversion sprains, one of the most common injuries among basketball players (Harmer 2005, Randazzo *et al.* 2010). These modifications include the high-top collar height which was designed to improve ankle stability and prevent ankle injury. It is thought that high-top basketball shoes provide a mechanical barrier that limits inversion, although the effectiveness of high-top shoes in preventing ankle injuries is uncertain (Garrick and Requa 1973, Rovere *et al.* 1988, Barrett *et al.* 1993). One obstacle to determining the effect of high-top shoes is the difficulty in measuring the motion of the ankle inside the shoe. Shoe inversion (i.e., motion of the heel counter relative to the lower leg or ground) has been measured in several biomechanical studies that compared high-top and low-top shoes (Stacoff *et al.* 1996, Avramakis *et al.* 1999, Ricard *et al.* 2000, Bing *et al.* 2007, Yu *et al.* 2007). However, previous research has shown that measures of shoe inversion are not the same as measures of ankle inversion inside a shoe (Stacoff *et al.* 1996, Avramakis *et al.* 1999), and thus the ideal experimental approach would be one that involved measuring ankle inversion inside the shoe. Unfortunately, measuring ankle inversion inside the shoe is difficult, and previously reported techniques are not without limitations. For example, previous studies have used high speed video to record the position of markers that were secured directly to the heel after cutting holes in the shoe (Stacoff *et al.* 1996, Avramakis *et al.* 1999), but this approach likely compromises the structural integrity of the shoe. Optical motion capture systems have also been used to record the position of markers secured to intracortical bone pins that were inserted into the calcaneus and tibia (Stacoff *et al.* 2000), but it is likely that the bone pins compromise the integrity of the shoe and potentially inhibit normal motion. Similarly, the approach described by Eils and Rosenbaum for assessing the efficacy of ankle braces measured ankle inversion with a goniometer attached to the lower leg and heel cap, but it is likely that this experimental approach may also alter normal motion during activities such as an aggressive cutting (Eils and Rosenbaum 2003).

The primary objective of this study was to compare ankle inversion to shoe inversion in both a high-top and a low-top shoe. A dynamic x-ray imaging technique was used to measure ankle in/eversion inside a high-top and a low-top shoe during a cutting movement without compromising shoe integrity. We hypothesised that ankle inversion would be lower than shoe inversion in both the high-top and low-top conditions. A secondary objective of this study was to assess differences between the

*Corresponding author. Email: jennifer.bishop@nike.com

high-top and low-top conditions in terms of shoe inversion and ankle inversion.

2. Methods

Following approval by an ethics review board and informed consent, eight male basketball players were recruited to participate in the study. However, there were not sufficient data for two of the subjects in one of the shod conditions. Data from six subjects (age: 21.2 ± 3.2 years, mass: 79.2 ± 9.9 kg, height: 1.86 ± 0.04 m) were used for analysis. A post-hoc power analysis of ankle inversion compared to shoe inversion for the high-top and low-top indicated that a sample size of 6 subjects provided for 90% power ($\alpha = 0.05$, $\beta = 0.20$). All subjects played basketball at a competitive level on a regular basis (average times per week: 1.8 ± 1.3). Potential subjects were excluded if they had ever experienced severe trauma or surgery to the ankle. All subjects were required to be free from injury with no symptoms for one year.

In order to measure motion of the rearfoot, lower leg, and shoe, radio-opaque beads (2 mm diameter) were attached to the skin and shoe. To assess motion of the lower leg, two beads were placed approximately 2.5 cm apart along the Achilles tendon. To minimise the effects of skin movement and shoe deformation on measures of ankle inversion and shoe inversion, four beads were attached in pairs on both the top and bottom of the calcaneus and the back of the shoe (Figure 1). Calcaneus markers were consistent within subject for both conditions and any errors in alignment with the vertical plane were systemic between the high-top and low-top conditions. Marker locations on the back of the high-top and low-top shoes were referenced to the vertical plane in each subject's own standing trial for each condition.

Subjects performed an aggressive lateral cutting movement inside the field of view of a custom x-ray imaging system. The x-ray system consisted of a 100 kW x-ray generator (EMD Technologies CPX 3100CV) operating in pulsed mode at 170 Hz and an image intensifier (Thales 9447 QX H404 L VR70), optically coupled to a synchronised high-speed video camera (Phantom v9.1, Vision Research) that acquired images at 170 Hz. The cutting movement included a three step run up and run out. During the 90-degree directional change step, the long axis of the subject's right foot was parallel to the custom imaging system's x-ray beam. Alignment of the foot was measured using markers placed on the first and fifth metatarsal heads. All trials used for analysis were within ±5° of the imaging axis, which has been considered to be the acceptable range by previous research (Stacoff *et al.* 1996). Five cutting trials and a standing trial were collected in two different footwear conditions for each subject: low-top shoe (Nike Hyperdunk Low) and high-top shoe (Nike Hypermax TB). Three cutting trials from each subject were used for analysis.

The two-dimensional (2D) location of each marker bead was measured from the x-ray images using TrackEye Motion Analysis software (Photo-Sonics, Inc., Burbank, CA). Measurements were limited to the portion of stance phase from just after heel-strike to just before heel-lift (approximately 10–80% of the stance phase). The decision to eliminate the early part of stance was based on pilot work comparing the motion of the tibia to the beads on the skin of the lower leg. This work indicated that the vast majority of relative skin motion occurred within the first 10% of the stance phase. Once the initial portion of stance was disregarded, relative motion between the skin markers and the underlying bone was minimal. The latter portion of stance phase from when the heel began to lift onward (approximately 80–100% of the stance phase) was eliminated given that we were most interested in the support phase of the cutting movement. Unfiltered data were used for analysis.

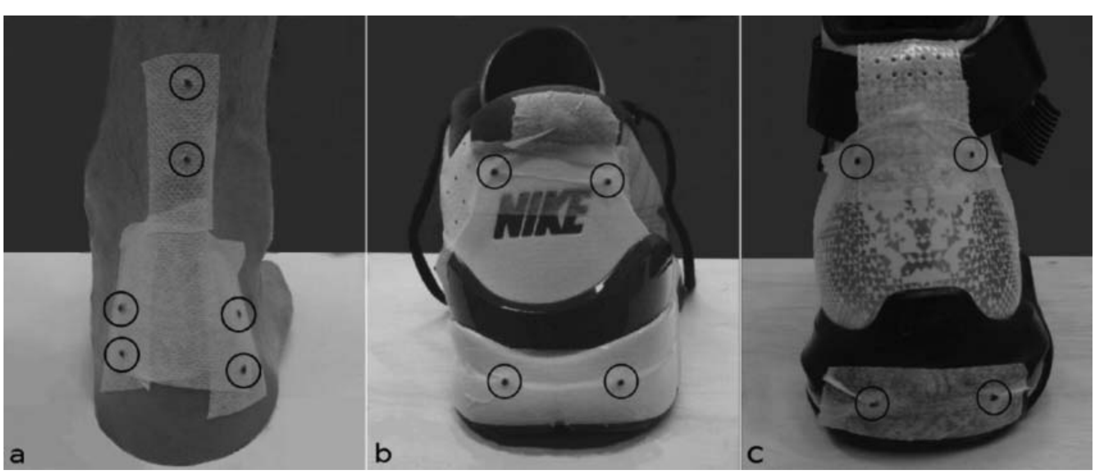

Figure 1. Location of beads on the rearfoot and shoes used to measure relative motion.

Figure 2. Representative x-ray image showing beads used to measure rotation of shank, rearfoot, and shoe.

The outcome measures that were determined included the ankle inversion angle, shoe inversion angle, and shank angle. Ankle inversion angle was calculated as the angle between: 1) a line connecting the midpoint of the beads on the back of the heel, and 2) a line connecting the beads on the lower leg (Figure 2). Shoe inversion angle was calculated in a similar manner using markers attached to the heel counter (Figure 2). Shank angle – a measure used to assess consistency of the cutting motion between the barefoot and shod conditions – was calculated as the angle between a line connecting the beads on the lower leg and vertical.

The maximum and range (maximum minus minimum value) of each outcome measure (ankle inversion angle, shoe inversion angle, shank angle) was determined for each trial and then averaged across trials for each subject. We then averaged these data across subjects to produce an average maximum and average range for each outcome measure. It was thought that shoe height might limit motion at the extremes of inversion/eversion. Therefore, we anticipated that differences between high-tops and low-tops would be manifested in ranges of motion. Paired *t* tests (alpha = 0.05) were used to compare the subject means for shank angle and to compare the ankle inversion angle to the shoe inversion angle for both the high-top and low-top condition.

Table 1. Average maximum and range values (n = 6) for shank angle, ankle inversion, and shoe inversion (degrees) for the low-top and high-top. †denotes significant within shoe difference between ankle inversion and shoe inversion.

	Maximum		Range	
	Low-Top	High-Top	Low-Top	High-Top
Shank Angle	36.0 ± 6.3	39.4 ± 6.7	11.1 ± 3.8	14.2 ± 3.8
Ankle Inversion	10.0 ± 7.1	13.1 ± 7.5	10.8 ± 6.0	11.5 ± 4.2
Shoe Inversion	35.5 ± 5.5	30.1 ± 5.0	13.5 ± 4.0	12.2 ± 4.0
	†p = 0.0006	†p = 0.0004	p = 0.06	p = 0.48

Supplemental videos illustrating the methodology are available online at: http://dx.doi.org/10.1080/19424280.2013.834981

3. Results

No difference in cutting technique between high-top and low-top conditions was observed, as the study failed to detect a significant difference in shank angle between footwear conditions. Specifically, the maximum shank angle was not significantly different between the high-top (39.4 ± 6.7°) and low-top (36.0 ± 6.3°) shoes during cutting (p = 0.52, Table 1, Figure 3). Similarly, there was not a significant difference in the range of shank angle between the high-top (14.2 ± 3.8°) and low-top shoes (11.1 ± 3.8°, p = 0.28, Table 1).

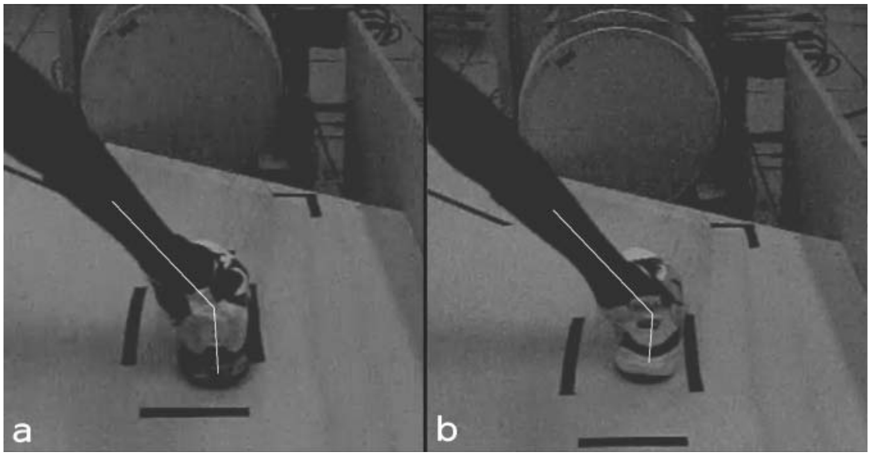

Figure 3. High-speed video stills of representative trials illustrating shoe inversion of the low-top (a) and high-top (b) during cutting.

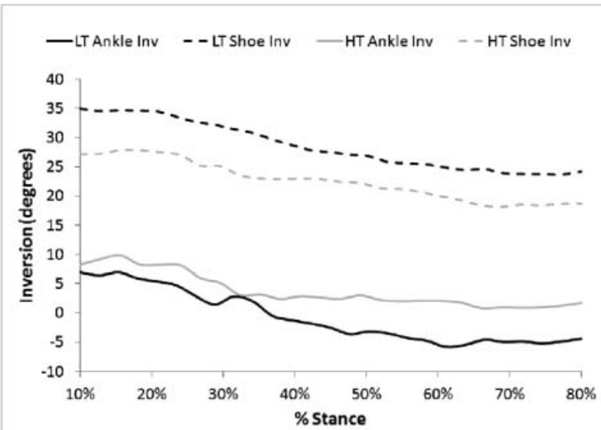

Figure 4. Representative trial showing the ankle inversion and shoe inversion angles for the low-top (LT) and high-top (HT) shoes over the portion of stance phase analysed. Unfiltered data shown and used for analysis.

Shoe inversion was significantly higher than ankle inversion for both the high-top (13.1 ± 7.5° and 30.1 ± 5.0°, p = 0.0004, Table 1) and low-top shoe (10.0 ± 7.1° and 35.5 ± 5.5°, p = 0.0006, Table 1). On average, shoe inversion was 17° greater in the high-top and 25.5° greater in the low-top than ankle inversion. There was no significant difference in range between the ankle and shoe inversion measurements for either the high-top (11.5 ± 4.2° and 12.2 ± 4.0°, p = 0.48) or low-top (10.8 ± 6.0° and 13.5 ± 4.0°, p = 0.06, Table 1). Ankle and shoe inversion angles during a representative cutting trial are shown in Figure 4.

4. Discussion

Shoe inversion is often used to assess the stability of a shoe. Coaches, trainers, and researchers alike have often utilised motion of the shoe relative to the shank as an indicator of inversion, and equated this to metrics of performance and/or risk of injury. However, results from the current study demonstrate that shoe inversion overestimates ankle inversion inside the shoe (17° greater in the high-top and 25.5° in the low-top). Therefore, shoe inversion cannot be considered to provide an accurate assessment of ankle inversion inside the shoe.

Data from a previous study by Avramakis and colleagues (1999) showed lower ankle inversion while wearing a high-top shoe compared to a low-top shoe. This study showed similar yet higher ankle inversion in the high-top compared to the low-top. This discrepancy could be due to differences other than collar height between the footwear used in that study and this study. Differences in the construction, such as upper, outsole and heel counter could affect the overall performance of the shoes and, therefore, motion at the ankle. Methodological differences could account for differing results. In the previous study, the authors cut holes in the shoes in order to view the rearfoot with video. This may have compromised shoe integrity and reduced how much effect the high-top had on the motion of the ankle. If a high-top shoe is designed to provide a closer fit over the ankle, cutting holes in the shoe would reduce this effect and could change the impact on the foot within the shoe compared to an intact shoe.

Previous research found lower shoe inversion in a high-top shoe compared to a low-top shoe during cutting movements (Avramakis *et al.* 1999) and during mechanically induced ankle inversion (Ricard *et al.* 2000). The current study showed similar yet lower shoe inversion in the high-top compared to the low-top. A future research study should include kinetics as well as kinematics of the ankle, knee, and possibly the hip to determine the full effect of the high-top shoe.

Additional research should be done to determine critical factors for predicting and/or preventing injury. Though results for the high-top and low-top shoes were similar, ankle inversion was slightly higher in the high-top than the low-top while relative motion of the shoe to the rearfoot was lower (Figure 4). The effect on injury risk of reducing ankle inversion inside the shoe versus limiting relative motion between the shoe and the rearfoot is not known. High-top shoes are designed to fit over more of the ankle and lower leg, and are thought to improve stability either by enhancing proprioception, or by increasing passive mechanical resistance to inversion (Shapiro *et al.* 1994, Ottaviani *et al.* 1995, You *et al.* 2004). However, previous studies examining injury risk in high-top and low-top shoes have not been conclusive (Barrett *et al.* 1993). It is possible that the higher collar height in a high-top shoe causes increased ankle inversion. Most footwear midsoles and outsoles are designed to be most stable when flat on the ground during the stance phase. As a shoe makes contact with the ground during cutting, the flat base and torsional rigidity of most footwear forces the shoe to rotate to this flat/static position. By design, the high-top shoe extends further up the leg than the low-top, which may act to force the subtalar joint into increased inversion as the shoe becomes flat on the ground in contrast to the angle of the leg. Further studies are needed to provide more insight into this comparison.

Given that there was not lower ankle inversion in the high-top shoe than the low-top shoe, it seems improbable that high-top shoes provide a mechanical advantage that prevents inversion injury. Ankle sprains occur as both contact and non-contact injuries, with the majority of ankle sprains occurring as a result of contact with another player (Dick *et al.* 2007). Though the potential mechanical advantage provided by the high-top shoe is likely too small to prevent inversion caused by landing on another player's foot, the mechanical advantage may be enough to prevent non-contact ankle inversion sprains. Previous research has shown that the main function of an ankle brace is to restrict ankle inversion during free fall (Eils and Rosenbaum 2003) and that more plantar flexion of the foot at impact leads to a greater risk of an ankle inversion sprain (Wright 2000). Further research is needed to study the influence of the high-top shoe on ankle inversion and plantar flexion before contact with the ground and the subsequent influence on risk of injury.

High-top shoes may provide a proprioceptive advantage over low-top shoes. Research suggests that deficits in ankle proprioception are predictive of ankle injuries (Payne *et al.* 1997, Willems *et al*. 2005, de Noronha *et al.* 2006). Adding compression around the ankle has been shown to improve ankle proprioception in some cases (Robbins *et al.* 1995, You *et al.* 2004, Miralles *et al*. 2010). Since the high-top covers more of the ankle it may improve proprioception. However, a study by Barrett and colleagues failed to detect a significant difference in the number of ankle injuries among basketball players when wearing high-top versus low-top shoes (Barrett *et al.* 1993). The high-top shoe may not provide enough compression around the ankle to improve ankle proprioception.

Although there are benefits to using x-ray imaging to measure motion of the foot inside the shoe, there are also limitations to this technique. One obvious limitation is radiation exposure to the subjects. Radiation exposure for each subject was less than 6.0 mSv, which is considered minimal risk according to the US Food and Drug Administration. Despite the low risk, to limit radiation exposure a small number of subjects were used. A future study with more subjects should be done to determine if there are significant differences in ankle inversion and shoe inversion between a high-top and low-top shoe.

Another limitation is that these results were based on 2D x-ray images. This narrowed the analysis to the portion of the stance phase before push off, when the foot was flat to the ground. However, this was justified since we were most interested in the support phase of the trial when inversion angles were the highest. In addition, since the shoe is a layer over the foot, the data could be affected by changes in foot orientation relative to the x-ray path. For this reason, trials where the foot was not in line with the imaging axis were not used. Even so, the potential for out-of-plane error is a limitation of this method.

Motion of the skin relative to the underlying bony structure of the foot is another potential source of error. However, based on pilot work, most skin artefact occurred in the first 10% of the stance phase, which was not used for analysis. To further reduce the possible effect of relative skin motion and shoe deformation, foot and shoe angles were calculated from the midpoint of measurements taken from the top and the bottom of the rearfoot and shoe.

The results were most likely affected by the specific footwear used. The shoes in this study were representative of current low-top and high-top basketball shoes with a heel counter. A limitation of this study is that the low-top and high-top shoes were not identical to each other in every way other than collar height. There were also differences in the upper and midsole construction of the shoes, which could have had an effect on these results. For example, the Hypermax TB has a full length airbag while the Hyperdunk Low has a predominantly foam midsole. Further research could be done to determine how specific footwear attributes affect the results. However, as footwear modifications continue to change, the effect on ankle inversion inside the shoe may need to be reassessed.

In conclusion, shoe inversion measurements do not mimic ankle inversion inside the shoe for either a high-top or low-top shoe. Further research needs to be done to determine the effect of ankle inversion versus motion of the shoe relative to the foot on injury risk.

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