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Ankle injuries are common. These injuries are often the result of excessive inversion at the subtalar joint. Previous research measuring shoe motion suggests that inversion at the ankle during cutting is as high as 40 degrees. However, this does not seem possible without injury. Some researchers have cut holes in shoes to view foot motion directly; however, this compromises the integrity of the shoe and potentially changes ankle kinematics. During barefoot cutting, ankle inversion has been measured directly showing that there is little or no ankle inversion. It is not known how footwear affects ankle inversion inside the shoe during cutting. The purpose of this study was to determine the effect of footwear on ankle inversion during aggressive lateral cutting without compromising shoe integrity. This was done using a dynamic x-ray imaging technique to measure ankle and shoe inversion while barefoot and shod. It was hypothesised that during aggressive cutting: 1) maximum ankle inversion would be the same in the barefoot and shod conditions, and 2) maximum shoe inversion would be significantly greater than maximum ankle inversion in the shod condition. During aggressive cutting, the maximum ankle inversion angle was 4.2 ± 3.5 degrees while barefoot and 11.7 ± 7.4 degrees while shod ($p = 0.009$), suggesting that the shoe does affect ankle inversion. Shoe inversion (38.3 ± 5.2 degrees) greatly overestimated ankle inversion inside the shoe ($p = 0.00003$). Therefore, shoe inversion measurements should not be used to represent ankle inversion during cutting movements. Ideally, the effect of specific footwear on ankle inversion should be assessed based on direct measurements of ankle inversion inside the shoe.

Keywords: in vivo kinematics; cutting; ankle inversion; x-ray imaging; barefoot

1. Introduction

Ankle strains and sprains are some of the most commonly occurring sports related injuries (Jago and Finch 1998, Adirim and Cheng 2003). These injuries are often the consequence of excessive inversion of the foot relative to the tibia at the subtalar joint. As a result, research has focused on ankle inversion during cutting movements as a way to evaluate stability and risk of injury in different footwear conditions. However, there are discrepancies in the inversion angle reported in these footwear studies, and it is not known if these differences are predominantly due to the effect of varying footwear conditions or differences in measurement technique. Results from high-speed video of the shoe have shown that the foot-shoe complex inverts about 42 degrees relative to the shank during cutting (Ricard *et al.* 2000, Yu *et al.* 2007). Optical motion capture measurements from reflective markers on the shoe and shank have shown an inversion angle of 21 degrees (McLean *et al.* 2005). Although these measurements may be useful in determining shoe stability, they do not give a direct measurement of ankle inversion. A cadaveric study found that the total passive range of motion for inversion of the foot relative to the shank was 16 degrees on average and 22 degrees at a maximum (Siegler *et al.* 1988). A barefoot cutting study (Jenkyn *et al.* 2010) and an internal pilot study of the bare foot suggest that during aggressive cutting maximum rearfoot inversion relative to the shank is only about 3 degrees. These results raise doubt that the high inversion angles measured from the shoe accurately reflect the motion of the ankle inside the shoe.

Alternative measurement protocols have been utilised to directly measure rearfoot motion while shod. These techniques required holes to be cut through the shoe to measure heel motion with video (Reinschmidt *et al.* 1992, Stacoff *et al.* 1996, Avramakis *et al.* 1999) or with optical motion capture of bone pins inserted into the calcaneus and tibia (Stacoff *et al.* 2000). Cutting holes in the shoes likely affects the integrity and stability of the shoe. Furthermore, although the use of bone pins may be appropriate for gaining insights during running, the dynamic motion of cutting likely requires increased motion of the underlying tissue of the foot which would be impeded by the bone pins, likely preventing the subjects from moving normally. In addition, extra motion of the foot relative to

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the shoe during cutting could require larger holes in the shoe, further compromising the integrity and stability of the shoe. Lastly, the use of bone pins is an invasive procedure that likely reduces the sample size of the study.

The objectives of this study were to: 1) determine the extent to which footwear affects ankle inversion, and 2) determine the extent to which shoe inversion reflects ankle inversion. Specifically, ankle inversion was measured with a dynamic x-ray imaging technique so that the motion of the foot inside the shoe could be determined without compromising the integrity of the shoe. These data were compared to measurements collected in the same manner on the bare foot. We hypothesised that during aggressive cutting: 1) maximum ankle inversion would be the same in the barefoot and shod conditions, and 2) maximum shoe inversion would be significantly greater than maximum ankle inversion in the shod condition.

2. Methods

Following approval by an ethics review board and informed consent, eight male basketball players were recruited to participate in the study. One subject did not have sufficient data for one condition and was not used for analysis. Data from seven subjects (age: 21.7 ± 3.2 years, mass: 82.5 ± 15.0 kg, height: 1.86 ± 0.04 m) were analysed. All subjects played basketball at a competitive level on a regular basis (average times per week: 2.6 ± 2.2). 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 foot, 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 medial and lateral edge of the calcaneus and on the back of the shoe (Figure 1).

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 pulsed (170 Hz) x-ray generator (EMD Technologies CPX 3100CV) 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 approximately parallel to the custom imaging system's x-ray beam. Five cutting trials and a standing trial were collected barefoot and in a low-top court shoe (Nike Hyperdunk Low) for each subject. Foam padding similar in durometer to shoe cushioning (Asker C hardness of 50) was firmly secured to the cutting surface for the barefoot trials. Three cutting trials from each subject were used for analysis.

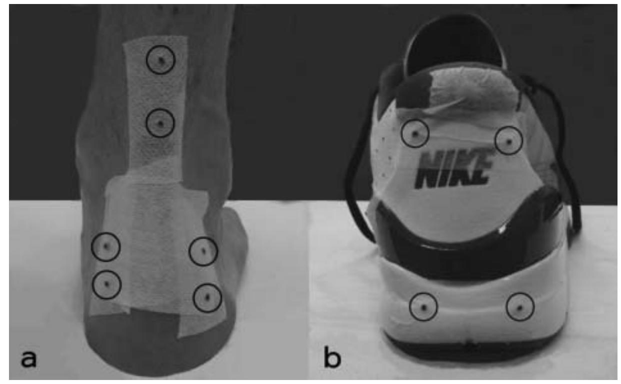

Figure 1. Location of beads on the lower leg and calcaneus (a) and the shoe (b) used to measure ankle and shoe inversion.

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). Trials where the foot was obviously not in line with the imaging axis were not used. Measurements were limited to the portion of the stance phase from just after heel-strike to just before heel-lift (approximately 10–80% stance phase). The decision to eliminate the early part of stance was based on the results of pilot work comparing the motion of the edge of the tibia bone to the beads on the skin of the lower leg (Figure 2a). Based on this work it was determined that most of the relative skin motion underlying the shank markers 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 in both the barefoot and shod conditions (Figure 2b). The latter portion of the stance phase from when the heel began to lift onward (approximately 80–100% of stance phase) was eliminated given that we were most interested in the support phase of the cutting movement. Unfiltered data were used for analysis.

The outcome measures that were determined included the ankle inversion angle (β), shoe inversion angle (γ), and shank angle (α) (Figure 3). The 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 4a). The shoe inversion angle was calculated in a similar manner (Figure 4b), using markers attached to the heel counter. 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.

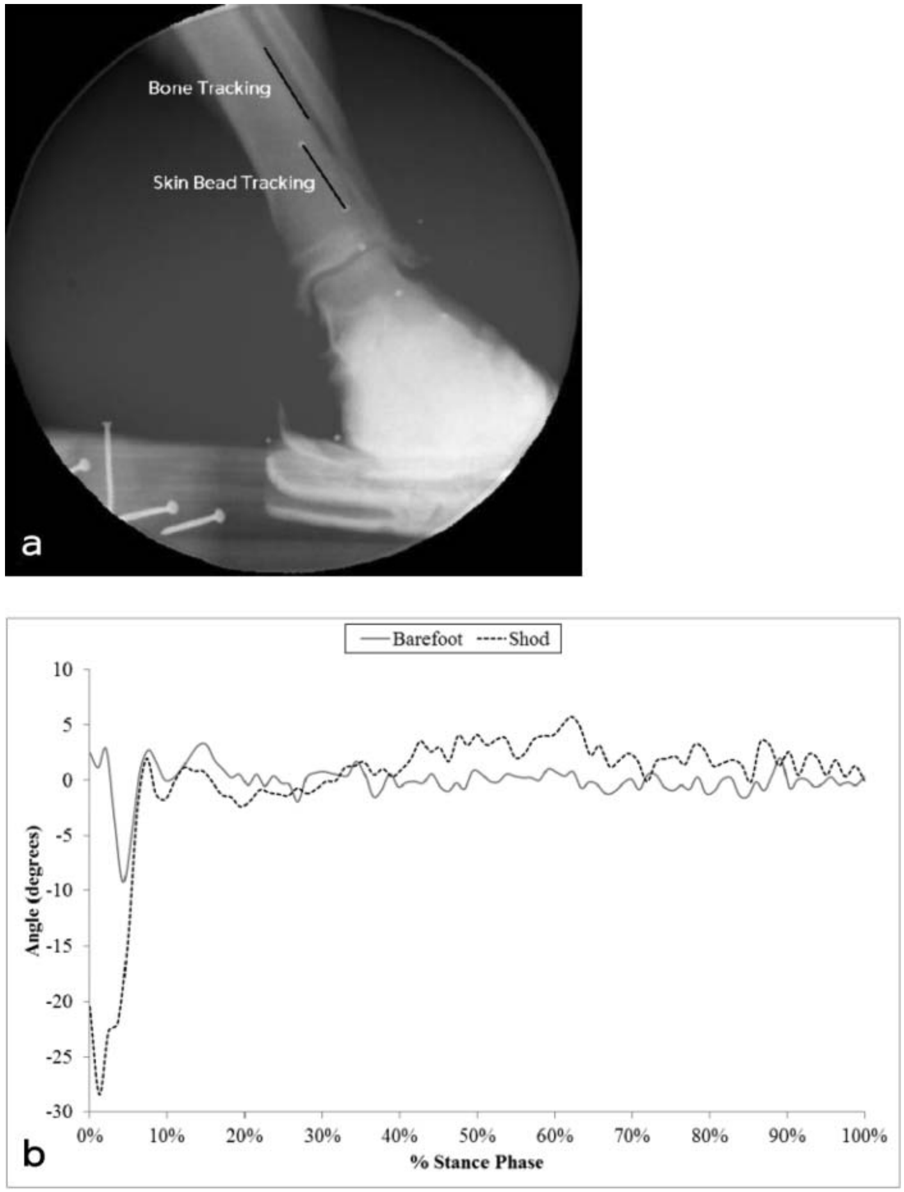

Figure 2. The angle between beads attached to the back of the lower leg and the edge of the tibia bone (a) was measured to determine the effect of skin artefact during the stance phase of a representative cutting trial (b).

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. The maxima were determined for each outcome measure, regardless of the timing. We then averaged these data across subjects to produce an average maximum and average range for each outcome measure. The range of the inversion angles throughout each trial was used as an indicator of variability between conditions not represented in the maxima (e.g. different contact angle). The angle of the rearfoot and the shoe relative to vertical at the time of the respective maximum inversion were calculated and averaged across subjects. Paired t tests ($\alpha = 0.05$) were used to compare the subject means for shank angle and ankle inversion angle across conditions (barefoot and shod). A paired t test ($\alpha = 0.05$) was also used to compare the ankle inversion angle to the shoe inversion angle for the shod condition.

Supplemental videos illustrating the methodology are available online at: DOI:10.1080/19424280.2013.834980

3. Results

In comparing barefoot cutting to shod cutting, it was observed that the subjects were performing the aggressive cutting motion differently between the barefoot and shod conditions. Specifically, the maximum shank angle in the

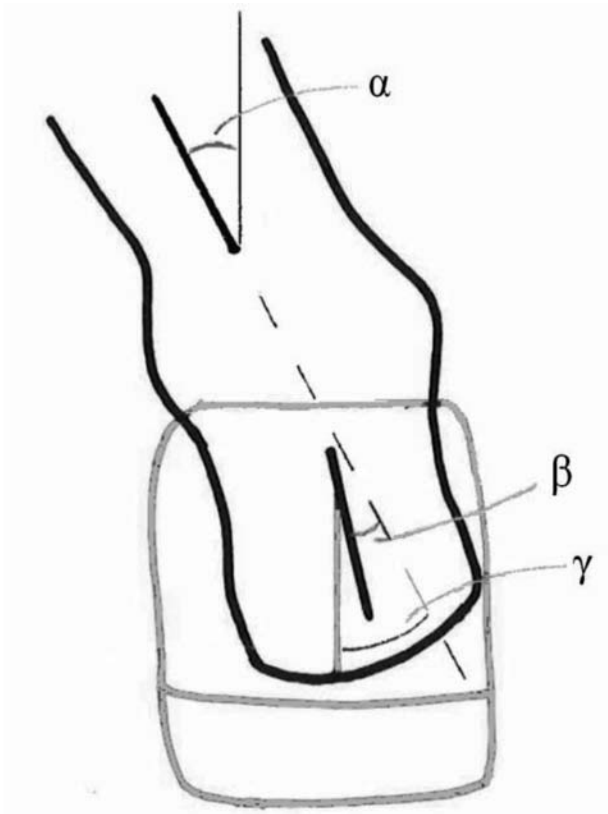

Figure 3. Diagram of rear view of the foot (black) and shoe (grey) illustrating the angles measured: ankle inversion (β), shoe inversion angle (γ), and shank angle relative to vertical plane (α).

shod condition (38.7 ± 4.0°) was significantly greater than the barefoot condition (29.2 ± 4.1°, $p = 0.004$, Figure 5) indicating that in the shod condition the subject's leg was angled further from vertical and out away from the body than when barefoot. The maximum ankle inversion angle in the shod condition (11.7 ± 7.4°) was significantly higher than in the barefoot condition (4.2 ± 3.5°, $p = 0.009$, Table 1). At the time of maximum ankle inversion the angle of the rearfoot relative to vertical was 25.6 (± 6.2°) and 21.6 (± 5.2°) for the shod and barefoot conditions, respectively. The range of shank angle in the shod condition (11.7 ± 4.2°) was not significantly different than in the barefoot condition (8.9 ± 2.1°, $p = 0.12$, Table 1). Similarly, the range of ankle inversion in the shod condition (10.6 ± 5.7°) was not significantly different than in the barefoot condition (7.8 ± 2.4°, $p = 0.17$, Table 1).

In comparing ankle-based and shoe-based measures of inversion angle, the study found that the maximum ankle inversion angle (11.7 ± 7.4°) was significantly lower than the maximum shoe inversion angle (38.3 ± 5.2°, $p = 0.00003$). At the time of maximum ankle inversion the angle of the rearfoot and the shoe relative to vertical was 25.6 (± 6.2°) and −0.6 (± 3.8°), respectively. On average, maximum shoe inversion overestimated maximum ankle inversion by 26.1 ± 6.3°. The range of shoe

Figure 4. Representative x-ray images showing the angles measured based on the location of beads placed on the back of the shank, rearfoot, and shoe during cutting when barefoot (a) and shod (b).

inversion angle was 12.6 ± 4.7°, while the range of ankle inversion angle was 10.6 ± 5.7° (Table 1, $p = 0.06$). Representative ankle inversion and shoe inversion data from a barefoot and a shod cutting trial are shown in Figure 6.

4. Discussion

The results do not support the first hypothesis that the ankle inversion angle measured when shod would be the same as when barefoot. However, maximum ankle

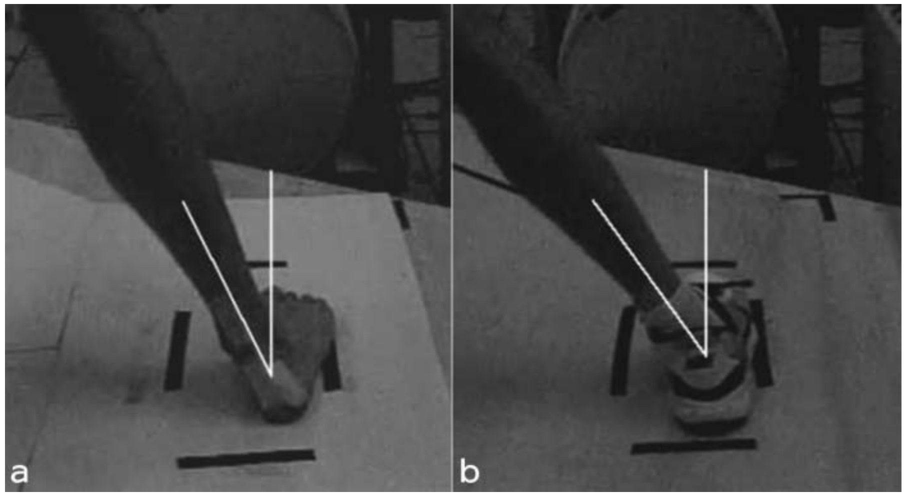

Figure 5. High-speed video stills during cutting in the x-ray field-of-view for one subject showing a representative difference in shank angle relative to the vertical plane when barefoot (a) versus shod (b).

Table 1. Average (± std dev, n = 7) maximum and range values for ankle inversion, shoe inversion, and shank angles for the barefoot and shod conditions (where applicable). †*denote significant difference between value for shoe inversion compared to shod ankle inversion

	Maximum			Range		
	Barefoot		**Shod**	**Barefoot**		**Shod**
Ankle Inversion (β)	4.2 ± 3.5°		11.7 ± 7.4°†	7.8 ± 2.4°		10.6 ± 5.7°*
		p = 0.009			p = 0.17	
Shoe Inversion (γ)			38.3 ± 5.2°†			12.6 ± 4.7°*
			†p = 0.00003			*p = 0.06
Shank Angle (α)	29.2 ± 4.1°		38.7 ± 4.0°	8.9 ± 2.1°		11.7 ± 4.2°
		p = 0.004			p = 0.12	

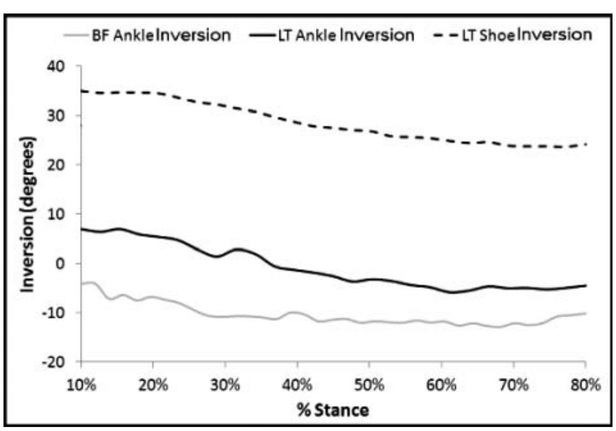

Figure 6. Ankle inversion and shoe inversion (when applicable) angles over time from representative cutting trials when barefoot (BF) and in a low-top shoe (LT) for the portion of the stance phase analysed.

inversion when shod (11.7°) was significantly higher than when barefoot (4.2°, p = 0.009). This could indicate that footwear causes increased ankle inversion compared to barefoot. The angle of the shank relative to the vertical plane was also higher when shod (38.7° shod, 29.2° barefoot), which suggests that the subjects were cutting differently in the shoes than when barefoot. One reason for these kinematic differences could be that shoes provide greater traction and protection from shearing of the skin than the bare foot, which may have allowed the subjects to cut more aggressively. All of the subjects in this study wear shoes on a regular basis and are likely more comfortable cutting while shod than while barefoot. Although subjects took practice cuts while barefoot until they felt comfortable with the movement, it is possible that they used a different cutting strategy while barefoot than while shod. Another reason for the difference in ankle and shank kinematics when shod compared to barefoot could be the specific structure of the shoe. Given these factors, it is important to directly measure ankle inversion when shod rather than relying on barefoot cutting research to assume the ankle inversion angle inside the shoe.

Results from previous studies have reported a wide range of ankle inversion angles: 42 degrees during cutting when measured from the shoe (Ricard *et al.* 2000, Yu *et al.* 2007), 22 degrees for maximum passive inversion from a cadaver study (Siegler *et al.* 1988), and approximately 3 degrees while cutting barefoot (Jenkyn *et al.* 2010). The results found here more closely agree with the cadaveric and barefoot results: ankle inversion was 4.2 degrees barefoot and 11.7 degrees shod. The large ankle inversion values previously reported may not be physically possible without causing injury. A study by Kristianslund and colleagues (2011) compared ankle kinematics of a normal sidestep movement to those of the same subject during an accidental ankle inversion sprain. These data showed an ankle inversion angle of 23 degrees during the injury trial compared to approximately 5 degrees in the non-injury trials. Although there are differences in range of motion between people, these results suggest that high inversion angles measured at the back of the shoe may not be possible without injury. Furthermore, measurements of shoe inversion likely do not represent the angle of the ankle inside the shoe.

As hypothesised, shoe inversion (38°) was not the same as the underlying ankle inversion angle (12°). During shod cutting, the medial portion of the shoe typically makes initial contact with the ground. The shoe inverts relative to the shank, until the shoe is flat (−0.6° from vertical). Although the shoe seems to have an effect on the rearfoot inside the shoe, the rearfoot does not follow inversion to the same extent as the shoe (25.6° from vertical shod, 21.6° from vertical barefoot). For this reason, the ankle inversion angle measured between the rearfoot and the lower leg is much lower and more realistic than the inversion angle measured between the back of the shoe and the lower leg. The shoe inversion results were similar to previous research reporting inversion angles between 30 and 45 degrees during shod cutting (Reinschmidt *et al.* 1992, Avramakis *et al.* 1999, Ricard *et al.* 2000, Yu *et al.* 2007). In addition to measuring shoe inversion, Reinschmidt *et al.* (1992) and Avramakis *et al.* (1999) also measured motion of the foot through holes cut in the shoes. Much like the current study, they found a reduction in inversion of approximately 15–20 degrees when measured at the ankle versus the shoe. These results support the idea that measurements taken at the back of the shoe should not be reported as a representation of ankle inversion during cutting as they overestimate the inversion angle of the rearfoot inside the shoe.

There were several limitations with this study. Perhaps the biggest limitation of the technique is radiation exposure to the subjects. Radiation exposure for each subject was less than 6.0 mSv. For comparison, the Health Physics Society (www.hps.org) reports that each person in the United States receives approximately 3.0 mSv of radiation exposure from background sources every year. According to the US Food and Drug Administration this amount of radiation exposure is considered minimal risk.

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 approximately 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. Previous research has shown that bone-based versus skin-marker-based measures of frontal plane motion of the calcaneus relative to the lower leg can differ by as much as 4.8 degrees (Nester *et al*. 2007). However, based on pilot work, most skin artefact occurred in the first 10% of the stance phase, which was not used for analysis (Figure 2). 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.

Finally, these results could have been affected by the design and construction of the footwear used and may not be representative of the results of footwear conditions with different heel counter stiffness, fit, outsole materials, etc. However, the shoe used here was representative of a current standard low-top court shoe with a heel counter.

Overall, this continuous x-ray method was successful in measuring ankle inversion inside the shoe without compromising the structure of the shoe. Furthermore, this was done during a dynamic, aggressive cutting movement. Although the experimental technique used here is certainly non-standard and not used extensively, this technique could be used in future research to better understand how footwear modifications affect foot, lower leg, and shoe kinematics and to determine the benefits of these footwear modifications in reducing ankle injury. Athletic footwear manufacturers currently use various construction methods to increase footwear stability and help prevent ankle inversion injuries, such as the heel counter and the high-top. Until other non-invasive methodologies are found, this non-standard x-ray technique could be used to determine the effect of these interventions on ankle inversion inside the shoe during aggressive cutting movements.

Another intervention that could be assessed is the use of orthoses. Orthoses are fit to the foot when it is in a static position and are often designed for linear motion. However, these orthoses are often used by athletes in multi-directional sports. The effect of orthoses in lateral movements is not well understood. Previous research by Yu and colleagues (2007) used in-shoe pressure and external shoe marker measurements to study the effect of wearing orthoses during a 180-degree shuttle cut. They found a significant increase in shoe inversion and pressure under the fifth metatarsal suggesting that the use of orthoses may increase the risk of injury. The non-standard x-ray technique from the current study could be used to further characterise the effect of orthoses on the dynamic motion of the foot inside the shoe during aggressive lateral movements.

In conclusion, the results of this study suggest that footwear does affect ankle inversion. Further research should be conducted to determine the extent to which different footwear modifications affect ankle inversion and the long term effectiveness at preventing injury, or affecting performance. However, since measures of shoe inversion have been shown here to be an inaccurate estimation of ankle inversion, foot motion inside the shoe should be measured directly to accurately assess the effects of footwear modifications on ankle inversion.

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