Effects Of Footwear on Three-Dimensional Tibiotalar and Subtalar Joint Motion During Running

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Introduction: Running is a popular activity for fitness and recreation, but running-related injuries affect 19-79% of runners every year [1-3]. Altered foot and ankle motion during running is believed to contribute to running-related injuries, but the relationships between joint motion and injury are not well understood. Previous studies investigating the effects of footwear on joint motion have typically relied on optical motion capture techniques, but these techniques have inherent accuracy limitations. Therefore, the objective of this study was to determine the effect of footwear on 3D in-vivo foot and ankle motion using a dynamic biplane x-ray system. We hypothesized that joint ranges of motion would be highest in the barefoot condition and lowest in the motion control shoe, and that motion patterns in the minimalist shoe would be most similar to the barefoot condition.

Methods: Following IRB approval and informed consent, 12 subjects (6 M, 6 F, age: 24±4) enrolled in this study. All subjects were recreational runners who averaged at least 25 miles/week and were injury free for the previous year. Subjects were tested in three footwear conditions: barefoot, minimalist shoes (Nike Free 3.0) and motion control shoes (Nike Structure Triax). Biplane radiographic images were acquired at 120 Hz as subjects ran at a self-selected pace along a custom elevated platform. Three trials per footwear condition were acquired for each subject. After testing, CT scans of the distal tibia and foot were acquired and reconstructed into 3D bone models for the calcaneus, talus, and distal tibia. 3D motions of the tibia, talus, and calcaneus were determined with model-based technique [4] and 3D rotations of the tibiotalar and subtalar joints were quantified in terms of plantarflexion/dorsiflexion (PF/DF), inversion/eversion (IV/EV) and internal/external rotation (IR/ER). 3D joint rotations were also normalized in 10% increments from foot strike (0%) to heel-off (100%). Joint ranges of motion (ROM) were also calculated for each trial. Differences between footwear conditions were assessed with a one-way ANOVA with repeated measures and Bonferroni post-hoc comparisons. Significance was set at p<0.05.

Results: Tibiotalar Joint: The ranges of PF/DF and IR/ER were significantly greater in the barefoot condition (PF/DF: 28.2 ± 8.3°; IR/ER: 7.0 ± 1.4°) compared to both the minimalist (PF/DF: 15.1 ± 5.9°; IR/ER: 4.8 ± 2.1°) and motion control (PF/DF: 15.0 ± 6.2°; IR/ER: 4.4 ± 1.0°) conditions (p<0.01). No differences in IN/EV ROM were detected between footwear conditions (p=0.27). PF/DF was significantly less in the first 20% of the stance phase and significantly more in the last 20% of the stance phase in the barefoot condition compared to both the minimalist and motion control shoes (p<0.003, Figure 1). Differences in IN/EV were present in only the first 10% of the stance phase, with the joint exhibiting more inversion in the motion control shoe compared to the barefoot condition (p<0.04). IR/ER differences were detected in the first 40% of the stance phase, with significantly more internal rotation found in the barefoot condition compared to the minimalist and motion control shoes (p<0.003). Subtalar Joint: Differences at this joint were primarily between the two shoe conditions. Specifically, from 20-60% and 90-100% of the stance phase, the minimalist condition was significantly more dorsiflexed than the motion control shoe (p<0.01). From 10-40% of the stance phase, the joint was more inverted in the motion control shoe compared to the minimalist shoe (p<0.01). The only significant difference detected in IR/ER was at 30% of the stance phase, with a more internally rotated position in the motion control compared to the minimalist shoe (p=0.004). No significant differences in subtalar joint ROM were detected between the three footwear conditions (p>0.05).

Discussion: The differences reported here occurred primarily at (or near) foot strike, and therefore may simply indicate differences in foot strike patterns between barefoot and shod running. This is especially true at the tibiotalar joint, where a less dorsiflexed position at foot strike in the barefoot condition may represent a more mid or forefoot striking pattern rather than the more traditional heel strike pattern that typically occurs in conventional running shoes. We expected that the minimalist shoe would also promote a mid or forefoot strike, but the data did not reflect this. Additionally, the kinematic differences at the subtalar joint were detected only between the two shoe conditions. The explanation for these differences is unclear, as foot strike patterns were relatively consistent between these two conditions. However, the differences in IN/EV between the shoe conditions seem to indicate that the primary restriction in a motion control shoe is a decrease in eversion at the subtalar joint in the early stages of the stance phase (first 10-40%). The implications of these findings with respect to running-related injuries is unclear; however, one purported benefit of barefoot running is a transition to a mid or forefoot strike pattern, decreasing the high impact forces on the heel. The results of this study show that while barefoot running does indeed result in a less dorsiflexed...
position at foot strike, the minimalist shoe does not. It is possible that this finding may change over time and that kinematics may more closely mimic barefoot conditions in response to a longer adaptation period, which is an avenue of further study. Additionally, future efforts could assess foot and ankle kinematics in injured runners, lending further insight into the complex relationships between joint motion, joint mechanics, and running-related injuries.

**Significance:** This study utilized a biplane x-ray imaging system to accurately and independently measure dynamic, in-vivo tibiotalar joint and subtalar joint motion, thereby overcoming many of the inherent limitations associated with conventional optical motion capture systems. The study indicates subtle differences in rearfoot motion between barefoot, minimalist, and motion control footwear conditions, and provides baseline data for future studies aimed at understanding the relationship between joint motion and running-related injuries.

**Acknowledgments:**


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**Figure 1.** The tibiotalar joint was significantly less dorsiflexed in the barefoot condition from 0-20% of the stance phase and significantly more dorsiflexed from 80-100% of the stance phase compared to the minimalist and motion control footwear conditions.

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