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Calcaneus range of motion underestimated by markers on running shoe heel

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ABSTRACT

Background: The measurement of rearfoot kinematics by placing reflective markers on the shoe heel assumes its motion is identical to the foot's motion. Studies have compared foot and shoe kinematics during running but with conflicting results. The primary purpose of this study was to compare shoe and calcaneus three-dimensional range of motion during running. A secondary purpose was to determine the effect of a less rigid heel counter on tibia motion.
Research question: Do markers placed on the shoe heel accurately represent calcaneus kinematics during running?
Methods: Three-dimensional coordinate data were collected on 14 subjects (M/F: 9/5) who ran on an instrumented treadmill at 3.35 m/s under four conditions: modified/intact neutral shoes, and modified/intact support shoes. Shoes were modified by placing holes through the heel to allow for shoe heel and calcaneus coordinate data to be collected simultaneously via reflective markers on the shoe and on the skin of the heel within the shoe. Calcaneus, shoe heel, and tibia ROM were calculated from 0 to 50% stance phase and compared across shoe conditions.
Results: Calcaneal frontal plane ROM was significantly greater than neutral and support shoe heel ROM ($p < 0.001$). Calcaneus ROM was also significantly greater than shoe heel ROM in the transverse ($p < 0.001$) and sagittal ($p < 0.001$) planes. No change in tibial transverse plane ROM was observed ($p = 0.346$) across shoe heel conditions.
Significance: Shoe markers significantly underestimated calcaneus ROM across all planes of motion. These findings suggest calcaneus kinematics cannot be accurately measured with markers placed solely on the shoe heel. Additionally, the required modifications to the shoe's heel had no effect on tibia ROM in the transverse plane.

1. Introduction

Running studies regularly investigate rearfoot motion due to its link to running injury. For example, excessive tibial internal rotation is coupled to calcaneal movement in the frontal and transverse planes, with implications for both typical and pathological running gaits [1–3]. Investigations into rearfoot motion often use reflective markers attached to the runner's shoe to estimate calcaneus kinematics. These methods are both noninvasive and have a short time requirement [4]; however, the use of shoe markers to estimate calcaneus kinematics assumes the motion of the shoe is identical to that of the foot [5]. Several studies have compared kinematic data collected directly from the calcaneus with that collected from shoe markers, yet there is disagreement on whether shoe markers accurately represent calcaneus motion in the frontal, sagittal, and transverse planes [6–10]. An investigation of calcaneus motion relative to the running shoe heel is needed to better interpret findings from the literature. In these studies, holes or "windows" were cut in the shoe heel to provide access to the foot within. The effect of this methodology on ankle kinematics has been indirectly investigated by Van Gheluwe et al. [11], who quantified changes in rearfoot frontal plane motion due to the heel counter rigidity. However, the effect of heel counter rigidity on knee kinematics is currently unknown.

Prior investigations suggest calcaneus motion is overestimated by shoe markers during running, but results focused primarily on frontal plane motion or did not control for confounding variables related to shoe design [6–10]. Several of these studies implemented bone pins when measuring calcaneus motion, and while the use of bone pins allows for a direct measurement of the calcaneus, study participants must often run at relatively low running speeds due to the procedure's invasive nature, discomfort, or the required local anesthetic [6,7,10,12].

The effect of such modifications on shoe deformation [13],

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kinematic data quality [14], and ankle kinematics [11] have been previously explored, but no studies have determined the effect of heel counter modification on lower leg kinematics during running. Excessive internal rotation of the tibia has been associated with common running injuries such as patella femoral pain syndrome and iliotibial band syndrome [15–17]. Additionally, the coupling relationship between the calcaneus, talus, and tibia suggests that changes in rearfoot motion can cause changes in more proximal segments [3]. Understanding the effect of placing holes in the heel counter of shoes on tibial kinematics may provide insight into the degree that such modifications can influence the overall function of footwear.

Therefore, the objectives of this study were to (1) use non-invasive skin markers to determine calcaneus three-dimensional ROM relative to the shoe heel during running, and (2) determine the effect of holes placed in the shoe's heel counter on the internal rotation of the tibia across two levels of shoe support (neutral/support). It was hypothesized that markers on a neutral and support shoes would underestimate calcaneus ROM in the frontal, sagittal, and transverse planes. It was also hypothesized that there would be an effect of Support Level (Neutral/Support) on frontal plane ROM, with support shoes decreasing calcaneus ROM due to the presence of a medial midsole support [18,19]. Lastly, it was hypothesized that holes in the shoe's heel counter would have no effect on tibia rotation, indicating that this particular function of the shoe was not significantly affected by the required shoe modifications.

2. Methods

2.1. Participants

Kinematic data were collected on 14 healthy participants who were habitual rearfoot strikers (M/F: 9/5) and recreational runners (29 ± 17.4 (± SD) miles per week). Mean participant age was 29 ± 6 years (± SD) and mean body mass was 66.0 ± 8.5 kg (± SD). This study was performed in accordance with all applicable ethical regulations and all participants were informed of the procedures and risks of the study and provided written consent. Participants were excluded from the study if they had experienced a lower extremity injury in the past 6 months.

2.2. Materials

The shoes tested in this study (size M9 (EU42.5), W8.5 (EU40)) were custom designed and differed only in midsole density. Neutral shoes consisted of a full-length, single density midsole and support shoes had a medial post in the midfoot area. The midfoot post consisted only of a higher density foam, with no difference in the midsole's overall shape or color. These shoes were selected to control for differences in upper design, stack height, heel/toe drop, and outsole design, while isolating the midsole design differences between conditions. To access the foot within the shoe, a simple rotary tool (Dremel, Illinois, USA) was used to cut three oval holes into the right heel of each shoe according to established dimension guidelines [13]. The orientation and position of holes were maintained between shoes by applying a stencil to each shoe prior to holes being cut. All participants ran in a total of 4 shoe conditions: Intact neutral shoes (N_I), neutral shoes with holes (N_H), intact support shoes (S_I), and support shoes with holes (S_H).

Right foot three-dimensional kinematic data were collected using an 8-camera motion capture system (Motion Analysis Corp., Santa Rosa, CA, USA) at 250 Hz while participants ran on an instrumented treadmill (Bertec, Columbus, OH, USA) collecting data at 2000 Hz. Retroreflective markers fixed to custom lightweight plastic supports (skin markers) tracked the movement of the calcaneus within the shoe for N_H and S_H conditions (Fig. 1).

The marker set used in the present study to measure heel kinematics inside the shoe was based on the Rizzoli multi-segment foot model modified by Leardini et al. [20]. Additionally, three markers were attached to the shoe's heel counter in order to simultaneously measure the orientation of the shoe relative to the calcaneus inside of it. Therefore, three markers were used to define each of the shoe heel and calcaneus segments respectively, with skin markers placed in the center of each hole cut into the shoe (Fig. 2) [14]. The base of each skin marker support was left adhered to the participant's calcaneus between conditions to maintain consistent marker placement. A standing static trial was collected with markers placed on the malleoli and femoral epicondyles to define the reference frame for the calcaneus, shoe heel, and tibia. This standing trial was used to set a zero angle for all angles reported here. A small rigid marker plate with a cluster of four markers was also adhered to the shank to measure tibia kinematics during running.

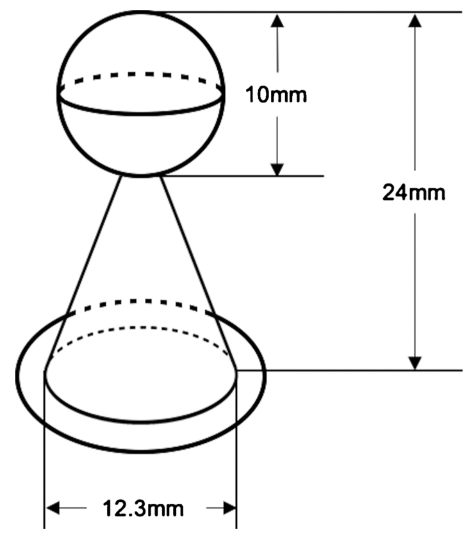

Fig. 1. Dimensions of skin marker supports for N_H and S_H conditions.

2.3. Experimental design

Participants initially ran on the treadmill for 5 min at 3.35 ms^{-1} to warm up and become familiarized with the testing environment prior to data collection. Following the placement of retroreflective markers, participants ran at 3.35 ms^{-1} for 2 min in each of the randomized conditions. Kinematic data were collected during the final 10 s of each trial. For N_H and S_H conditions, a high-speed camera (Nikon Phantom Miro M120) placed behind the treadmill recorded the movement of skin markers during stance phase at 800 Hz. Footage was immediately analyzed to verify that the skin marker supports did not come in contact with the edge of the holes. If this situation arose, the marker was reattached and the trial was repeated.

2.4. Data analysis

Kinematic marker data were smoothed in MATLAB (Version 2016b, Mathworks, Natick, MA, USA) using a dual-pass, low-pass Butterworth filter with a cut-off frequency of 12 Hz. In the global coordinate system, the Y-axis was defined in the anterior-posterior direction, the X-axis was perpendicular to the Y-axis in the horizontal plane, and the Z-axis was defined vertically. Local coordinate systems for the shoe heel and calcaneus segments were both defined by three markers following the method implemented by Trudeau et al. [10]. Local coordinate systems for the tibia were defined by the marker cluster on the shank and static markers on the proximal and distal ends of the tibia. The Z axis was defined as the vector from the midpoint between the lateral and medial malleolus to the midpoint between the lateral and medial femoral epicondyles. The Y axis was calculated normal to the frontal plane

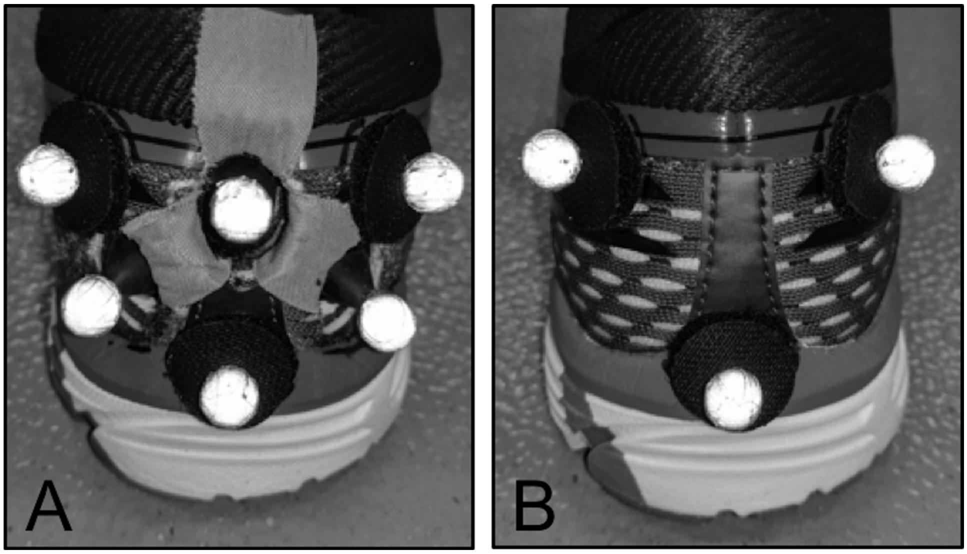

Fig. 2. (A) Orientation of rearfoot markers for NH and SH conditions, (B) Orientation of rearfoot markers for NI and SI conditions.

defined by the four tibial bony landmarks. The X axis was calculated as the cross product of the Y and Z axes, in the medial lateral orientation. All 3D segment angles were calculated relative to the global coordinate system from the Euler angles of the rotation matrices describing the orientation of the segments. The order of rotations used when computing the Euler angles relative to the anatomical planes was sagittal, transverse, frontal. Stance phase data were interpolated, normalized to 101 data points, and averaged across 10 steps for each participant.

It is important to note that the present study reports calcaneus, shoe, and tibia segment motion in the global coordinate system rather than joint angles. The joint angle approach requires the calculation of the distal segment's movement relative to the proximal segment, which may make comparisons in the same plane of motion more difficult if motions occur simultaneously [3,21]. The focus of the present study was the individual segments of the calcaneus, tibia, and shoe heel and as such, segment ROM in the global coordinate system were reported.

Kinematics were analyzed from 0 to 50% stance phase to determine shoe heel and calcaneus ROM, calculated by the difference between the maximum and minimum angle of the respective segment in the global coordinate system. The first half of stance phase was analyzed because the present study sought to focus on the kinematic changes occurring immediately after heel strike. The beginning of stance phase was defined as the frame where the vertical ground reaction force exceeded 50 N and ROM was determined for frontal, sagittal, and transverse planes, translating to rearfoot eversion, flexion, adduction, and tibial internal rotation. Shoe heel and tibia ROM was calculated for all conditions and calcaneus ROM was calculated for N_H and S_H conditions.

Repeated-measures ANOVAs were performed to investigate main effects of Marker Set (Calcaneus/Shoe Heel/Tibia), Support Level (Neutral/Support), and Heel Counter (Intact/With Holes) on ROM, as well as any 2-way interactions between Marker Set or Heel Counter and Support Level. Statistical significance was set at $p < 0.05$ and all statistical analyses were conducted using RStudio software (Boston, MA, USA).

3. Results

3.1. Support level * marker set (Calcaneus)

There were no significant interactions between Marker Set and Support Level in the frontal, sagittal, or transverse plane ($p = 0.141$, $p = 0.483$, $p = 0.409$). There were significant main effects of Support Level ($p = 0.021$) and Marker Set ($p < 0.001$) on frontal plane ROM. In the frontal plane, mean calcaneus ROM was greater than shoe heel ROM by 1.5°. There was no main effect of Support Level on transverse plane ROM ($p = 0.380$) and sagittal plane ROM ($p = 0.580$). There were significant main effects of Marker Set on sagittal plane ROM ($p < 0.001$) and transverse plane ROM ($p < 0.001$), indicating mean calcaneus ROM was greater than shoe heel ROM by 5.9° in the sagittal plane and 1.6° in the transverse plane (Table 1).

3.2. Support level * heel counter (Tibia)

There was no significant interaction between Heel Counter and Support Level ($p = 0.927$) in the transverse plane. There were no significant main effects of Heel Counter ($p = 0.346$) or Support Level ($p = 0.460$) on tibia ROM in the transverse plane. Therefore, the changes in heel counter and midsole design did not affect tibial internal

Table 1
Comparison of rearfoot 3-dimensional range of motion values across conditions.

Support Level * Markerset (Rearfoot)		Frontal Plane ROM [°]			Sagittal Plane ROM [°]			Transverse Plane ROM [°]		
		p	*M*	*SD*	*p*	*M*	*SD*	*p*	*M*	*SD*
Interaction Effect		0.141			0.483			0.409		
Main Effect										
Marker Set	Shoe Heel	< **0.001**	8.0	3.5	< **0.001**	17.6	8.8	< **0.001**	1.6	0.9
	Calcaneus		9.5	3.5		23.5	10.4		3.2	1.7
Support Level	Neutral	**0.021**	9.2	3.5	0.580	20.7	10.3	0.380	2.5	1.9
	Support		8.3	3.6		20.4	10.0		2.3	1.1

rotation ROM.

4. Discussion

The primary aim of the present study was to determine differences between shoe-mounted and skin marker 3D ROM during running. It was hypothesized that shoe markers would underestimate calcaneus ROM and the results support this hypothesis. Shoe markers significantly underestimated calcaneus ROM across all planes of motion by 1.5–5.9°. Additionally, neutral shoe ROM was greater than support shoe ROM by 0.9°, suggesting the medial post in the support shoe reduced calcaneus frontal plane ROM. The secondary aim was to investigate the effect of holes placed in the shoe's heel on tibial rotation. It was hypothesized there would be no change in tibial rotation ROM across shoes with or without holes in the heel. The results also support this hypothesis as tibia transverse plane ROM did not change.

4.1. Calcaneus and shoe heel ROM

The present study provides evidence that shoe-mounted markers are not representative of calcaneus motion compared to skin-mounted markers. While this conclusion corroborates those of prior investigations, the findings of the present study differ from Reinschmidt et al. [7], Stacoff et al. [8] as shoe markers were found to underestimate calcaneus motion (Table 1). In agreement with Sinclair et al. [9], the findings of the present study indicate calcaneus marker ROM was greater than shoe marker ROM by 1.5° in the frontal plane. Conversely, Reinschmidt et al. [7] and Stacoff et al. [8] found shoe marker peak eversion to be 5–20° greater than when measured via bone pins. The conflicting findings may be due to differences in how the shoe heel was modified in each study. For example, the present study and Sinclair et al. [9] followed guidelines by Shultz & Jenkyn [13] and Bishop et al. [14] to minimize the effect on shoe structural integrity while Reinschmidt et al. [7] removed the entire heel counter to ensure the shoe did not inhibit bone pin movement. The greater degree of shoe heel modification may have diminished the coupling between the shoe and calcaneus.

Although Trudeau et al. [10] found calcaneus ROM to be greater than shoe ROM in the frontal and sagittal plane, they found no significant difference between shoe and skin marker frontal plane ROM. The contrasting results may be due to the shoes tested in each study. Trudeau et al. [10] compared publicly available neutral and support shoe models while the present study included custom designed neutral and support shoes that differed only in midsole design. This improved methodology effectively isolated a single variable in the footwear construction, allowing for comparisons to be made between shoes with and without a medial post, generalizable beyond a footwear brand or model. Considering many footwear-related studies compare conditions that are publicly available, such findings are inherently shoe-specific and may be confounded by the variety of differences between conditions. Although the primary difference between the two models tested by Trudeau et al. [10] was the presence of a medial post in the support shoe, differences in upper design, heel/toe drop, and midsole design were not controlled. It is possible these confounding variables influenced the potential difference between the two models, resulting in no observed difference in calcaneus frontal plane ROM relative to the shoe heel.

4.2. Tibial rotation ROM

It was suggested the placement of holes in the shoe's heel may decrease the rigidity of the heel counter, with larger holes resulting in greater changes in heel counter stiffness [6]. The data suggest that tibial rotation ROM was unaffected by changes in heel counter rigidity caused by holes in the shoe heel (Table 2). This finding was consistent across neutral and support shoes, as there was no effect of Support Level on tibial rotation ROM (Fig. 3). There was a significant main effect of Support Level on calcaneus frontal plane ROM but no main effect on sagittal or transverse plane ROM, suggesting the medial post effectively reduced calcaneus eversion. Although calcaneus eversion (frontal plane rotation) plays some role in tibial rotation [22], Fischer et al. [3] found that calcaneus transverse plane motion is more closely coupled with tibial rotation compared to calcaneus frontal plane motion. The findings of Fischer et al. [3] are supported by those of the present study as Support Level had no significant effect on calcaneus or tibia ROM in the transverse plane.

Table 2
Comparison of tibia 3-dimensional range of motion values across conditions.

Support Level * Heel Counter (Tibia)		Transverse Plane ROM [°]		
		p	*M*	*SD*
Interaction Effect		0.927		
Main Effect				
Heel Counter	Holes	0.346	11.6	5.7
	Intact		11.9	6.1
Support Level	Neutral	0.460	11.6	6.0
	Support		11.9	5.8

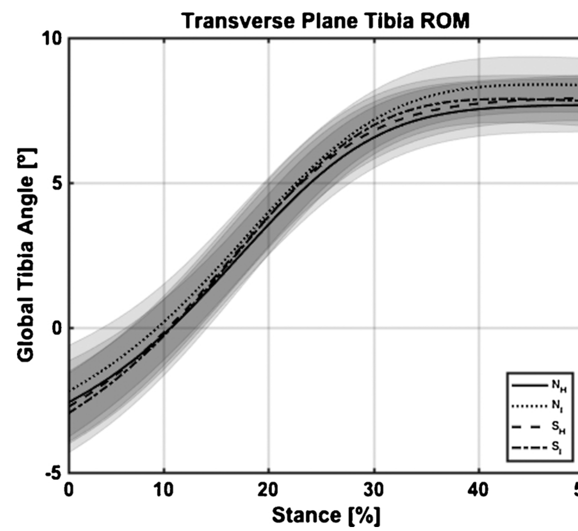

Fig. 3. Mean ± SD global tibia angles across all participants across conditions (positive is internal rotation).

It is important to consider the results of this study alongside possible limitations. The use of kinematic markers attached to the skin requires the placement of holes in the shoe heel, and findings pertaining to shoes with holes in the heel may not necessarily hold true for shoes with an intact heel. No significant changes in the frontal or sagittal plane ROM ($p = 0.190$, $p = 0.343$) were found following shoe heel modifications, yet small changes (0.3°) in the transverse plane were statistically significant ($p = 0.044$) when controlling for Support Type. While statistically significant, the clinical significance of a 0.3° difference in shoe heel ROM is unclear as shoe markers may only provide a description of gross motion [6].

Additionally, the skin moves relative to the calcaneus during running and therefore influences skin marker movement [23]. Soft tissue artefact (STA) is a source of error present in all human kinematic analyses where makers are used, with the effect of STA on depending on the location of markers and the motion performed [24]. However, this movement artefact caused by the soft tissue covering the posterior aspect of the calcaneus is likely small compared to that of other biomechanically relevant skeletal segments (e.g. femur) where there is a large amount of soft tissue present [25,26]. The sample of runners included in any study presents inherent limitations. The inclusion of only rearfoot strikers suggests that findings of the present study are only generalizable to approximately 75–98% of the running population [27–30]. Additionally, the strength of the coupling relationship between the calcaneus and tibia was not controlled across participants in the present study.

5. Conclusions

The present study adds to the current literature a comparison of 3D calcaneus motion relative to neutral and support shoes, as well as an investigation of how shoe heel modifications affect tibial rotation. Given that shoe markers significantly underestimated calcaneus ROM across all planes of motion, it is concluded that shoe markers did not best represent calcaneus motion compared to skin markers and that there may be a need to differentiate between shoe and calcaneus kinematics in biomechanical studies. No changes in tibial transverse plane ROM were observed following heel counter modifications, suggesting any changes in heel counter rigidity caused by the modifications had no effect on tibial rotation. These findings should be considered by future studies investigating tibiocalcaneal motion, the biomechanical role of the heel counter, or those requiring similar shoe modifications.

Conflict of interest

The authors wish to confirm that MT and ER are currently employed at Brooks Running Company (Seattle, WA, USA). However, the results presented in this manuscript do not in any way represent a bias towards Brooks Running Company products over other brands.

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