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Sagittal subtalar and talocrural joint assessment between barefoot and shod walking: A fluoroscopic study

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A R T I C L E I N F O

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A B S T R A C T

Background: While wearing shoes is common in daily activities, most foot kinematic models report results on barefoot conditions. It is difficult to describe foot position inside shoes. This study used fluoroscopic images to determine talocrural and subtalar motion.

Research Question: What are the differences in sagittal talocrual and subtalar kinematics between walking barefoot and while wearing athletic walking shoes?

Methods: Thirteen male subjects (mean age 22.9 ± 2.9 years, mean weight 77.2 ± 6.9 kg, mean height 178.2 ± 3.7 cm) screened for normal gait were tested. A fluoroscopy unit was used to collect images during stance. Sagittal motion of the talocrural and subtalar joints of the right foot were analyzed barefoot and in an athletic walking shoe.

Results: Shod talocrural position at heel strike was 6.0° of dorsiflexion and shod peak talocrural plantarflexion was 4.2°. Barefoot talocrural plantarflexion at heel strike was 4.2° and barefoot peak talocrural plantarflexion was 10.9°. Shod subtalar position at heel strike was 2.6° of plantarflexion and peak subtalar dorsiflexion was 1.5°. The barefoot subtalar joint at heel strike was in 0.4° dorsiflexion and barefoot peak subtalar dorsiflexion was 3.5°. As the result of wearing shoes, average walking speed and stride length increased and average cadence decreased. Comparing barefoot to shod walking there was a statistical significance in talocrural dorsiflexion and at heel strike and peak talocrural dorsiflexion, subtalar plantarflexion at heel strike and peak subtalar dorsiflexion, walking speed, stride length, and cadence.

Significance: This work demonstrates the ability to directly measure talocrural and subtalar kinematics of shod walking using fluoroscopy. Future work using this methodology can be used to increase understanding of hindfoot kinematics during a variety of non-barefoot activities.

1. Introduction

Despite the fact that donning shoes is common during typical daily activities [1,2], intra-foot kinematic models are usually developed and reported on for the barefoot condition [3–5]. Understanding shod foot kinematics requires the description of foot/bone position inside footwear. This description has proven challenging using standard stereophotogrammetry techniques. Most external marker based studies in the current literature that report on shod foot mechanics use sandals [6–9], remove shoe material to expose the underlying anatomic area for marker placement [6,10], or place markers on the outer surface of the shoe [11–13]. While these approaches have increased understanding of shod foot mechanics, they have their limitations.

Sandals cannot be assumed to replicate shoes, as differences in foot biomechanics will occur due to the restriction of foot motion from upper shoe materials and lacing [14]. A 2009 study by Hagen and Hennig reported significant differences in maximum pronation velocity, and peak pressure at various foot locations dependent on shoe lacing pattern while running [15]. Shoes with windowing (holes cut into them to expose anatomic locations for marker placement) have also been found to alter the mechanical properties of the shoe. A 2012 study by Shultz and Jenkyn [16] determined that hole sizes larger than 1.7 × 2.5 cm would disrupt shoe integrity, and a 2006 study by Bulter et al. [17] reported a 10% reduction in heel counter stability from shoe windowing. In addition, attempts to measure intra-foot kinematics using external markers placed on the outer surface of a shoe have had

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methodological concerns. A 2011 study by Bishop et al. [1] reported static distances up to 16.7 mm between markers placed on the external surface of the shoe and the underlying anatomic landmark. These static discrepancies between marker placement and the underlying anatomy lead to dynamic kinematic differences as measured in a study by Reinschmidt et al. that reported tibiocalcaneal plantarflexion/dorsiflexion differences up to 8.1° between shoe mounted and bone mounted markers [18].

Recently, fluoroscopy has been used to overcome these challenges in using external marker based foot models to measure shod foot kinematics. The radiographic nature of fluoroscopy allows for real time dynamic visualization of the underlying anatomy with no footwear modifications. Several fluoroscopic studies appear in the literature reporting on barefoot walking kinematics [19–22], but very few report on shod kinematics [23,24]. In a 2014 study by Campbell et al. [23], tibiocalcaneal kinematics between barefoot and shod walking were compared for six subjects, though talocrural (talus relative to tibia) and subtalar (calcaneus relative to talus) motion were not measured. Wang et al. [24] compared talocrural and subtalar kinematics from barefoot and shod walking in four or 10 cm high-heels, however only six individual images were analyzed between heel strike and toe-off.

The purpose of the current study was to determine sagittal plane talocrural and subtalar kinematic differences between barefoot and shod walking in athletic shoes. Dynamic fluoroscopic imaging was used to determine talocrural and subtalar kinematics from heel strike to 80% stance. The kinematic model used in this study applies a combination of motion and fluoroscopic data, and has previously been used to describe barefoot [20] as well as Control Ankle Movement (CAM) boot walking [21].

2. Materials and methods

In this Institutional Review Board (IRB) approved study, 13 male subjects (mean age 22.9 ± 2.9 years, mean weight 77.2 ± 6.9 kg, mean height 178.2 ± 3.7 cm), screened for exclusion criteria gave written informed consent prior to being tested walking barefoot and in athletic walking shoes (New Balance Men's MW927 Health Walking Shoe, heel drop = 14 mm) (Fig. 1). Exclusion criteria included any significant injury to the foot/ankle or any previous lower extremity surgery (bilateral).

The data capture system consisted of a modified fluoroscopy unit [20] placed within an existing Vicon motion analysis system (Vicon Motion Systems, Inc., Oxford, UK). The fluoroscopy unit (OEC 9000, GE, Fairfield, CT) was modified so that the image intensifier and emitter could be set on opposite sides of the width of the walkway. Heel strike and toe-off events were detected using an embedded multi-axis force plate (AMTI, Watertown, MA).

The right leg and foot of each subject were instrumented with six reflective markers (diameter = 16 mm) in accordance with Table 1. For the shod trials, foot markers (calcaneal tuberosity and head of second metatarsal) were placed directly on the athletic walking shoe as close to their corresponding anatomic locations as possible. Fluoroscopic and motion data were collected simultaneously (120 Hz) as subjects walked along a custom walkway. Each subject completed five trials walking barefoot and five trials walking shod. Following dynamic data collection, static right foot x-rays were taken for each subject in both conditions (barefoot and shod) (Fig. 1).

Radiation restrictions obviated recollection of fluoroscopic data if there was improper foot placement in the capture volume. Because of this, not all 13 subjects had five trials of data for each condition. For the barefoot condition, subjects averaged 4.5 ± 0.5 trials; for the athletic walking shoe condition, subjects averaged 3.8 ± 1.3 trials. Subject foot placement also determined how much of stance phase could be analyzed for each trial collected. If the tibia vacated the fluoroscopic field of view during toe-off, the analysis stopped. For this reason, the kinematic analysis was limited to between heel strike and 80% stance. No portions of stance phase were analyzed for which fewer than ten subjects had data.

Fig. 1. Athletic walking shoe (top). Static x-ray in athletic walking shoe (bottom).

Table 1
External marker placement.

Marker Number	Marker Location
1	Medial femoral epicondyle
2	Lateral femoral epicondyle
3	Medial malleoli
4	Lateral malleoli
5	Calcaneal tuberosity
6	Head of 2^{nd} metatarsal

The kinematic model used in this study has been previously applied to describe barefoot talocrural and subtalar sagittal plane motion [20]. The model uses external marker position to define a tibial local coordinate system, and fluoroscopic markers to define the talar and calcaneal local coordinate systems. External markers (medial/lateral malleoli and medial/lateral femoral epicondyles) were used to define the tibial local coordinate system as only the very distal end of the tibia was fluoroscopically visible for much of stance. For the talus and calcaneus, two points of interest per bone (talus, calcaneus) were translated from pixel coordinates to motion analysis global coordinates using a method of global referencing. This method has previously been shown to have errors less than 2 mm with subject foot progression angles of ± 5° [20]. Average foot progression angle for the current study was 3.3° external for barefoot and 4.8° external for shod. These translated points of interest were defined in the sagittal plane of the foot and were then used to describe local coordinate systems for the talus and calcaneus. These local coordinate systems were used to calculate talocrural and subtalar sagittal plane kinematics, with motion defined as distal position relative to proximal. Kinematics were also calculated from the statically collected data, with the angles obtained in the barefoot trial serving as the neutral position. For this study, an average talocrural joint offset of 3.6° of plantarflexion and an average subtalar joint offset of 1.4° of dorsiflexion occurred from donning shoes. Kinematic repeatability using this system has been determined to be 1.06° [20]. All kinematic trials in this study were time normalized to stance phase. In addition, all kinematic trials were averaged within a subject and then among subjects for assessment of each tested condition (barefoot and shod). This was done to align with previous work and to reduce any noise reported in individual trials [21,25].

Temporal spatial parameters were calculated using Vicon Nexus. Heel strike and toe off events were identified using trajectories of the markers on the calcaneal tuberosity and the head of 2nd metatarsal, respectively. The identified events were used to calculate cadence while stride length was calculated based on the marker on the head of 2^{nd} metatarsal.

A statistical analysis was done comparing shod to barefoot kinematics as well as temporal spatial parameters. The four sagittal plane kinematic positions statistically analyzed were talocrural plantarflexion at heel strike, talocrural peak plantar flexion, subtalar dorsiflexion at heel strike, and subtalar peak dorsiflexion. These parameters where chosen based on previous reports that indicated the importance of initial contact and peak load response [13,26]. The three temporal spatial parameters statistically analyzed were walking speed, cadence, and stride length. Temporal spatial parameters were chosen in accordance with previous shod gait papers [10].

The Shapiro Wilk test was performed on each metric analyzed for testing the null hypothesis that differences between shod and barefoot were normally distributed. For metrics that were normally distributed, a paired *t*-test was performed with the null hypothesis that the true mean difference between shod and barefoot walking was zero. Statistical significance was declared at $p \leq 0.05$.

3. Results

Talocrural kinematics for both conditions are shown in Fig. 2. At heel strike, barefoot plantarflexion was 4.2 ± 4.8° and shod was -6.0 ± 5.3°. Barefoot peak plantarflexion was 10.9 ± 4.3° occurring at 11% stance, and shod peak plantarflexion was 4.2 ± 4.7° occurring at 16% stance.

Subtalar kinematics for both conditions are also shown in Fig. 2. At heel strike, barefoot dorsiflexion was 0.4 ± 1.4° and shod was -2.6 ± 2.4°. Barefoot peak dorsiflexion was 3.5 ± 1.9° occurring at 31% stance, and shod peak dorsiflexion was 1.5 ± 2.1° occurring at 26% stance.

Using the Shapiro Wilks normality test, all metrics analyzed were normally distributed. The temporal spatial parameters showed as a result of wearing shoes, average walking speed significantly increased by 0.04 m/s, average stride length significantly increased by 0.10 m, and average cadence significantly decreased by 4.74 steps/min (Table 2). All kinematic metrics analyzed showed statistically significant differences between shod and barefoot, (Table 2).

4. Discussion

The effects of wearing shoes on lower extremity kinematics and temporal spatial parameters has been well documented in the literature using standard stereophotogrammetry techniques. What the bones of the foot are doing within the shoe is relatively unknown. This paper has presented a method of measuring sagittal plane motion of talocrural and subtalar joint motion during shod gait. This allows for measurement of true dynamic bony motion within the shoe.

The current study showed general agreement with previously published results of shod walking. The temporal spatial results compare favorably to previous studies and confirm that the natural response to footwear is an increase in walking speed and stride length, with a reduction in cadence [10,27]. Previous literature has shown the effect of shoes to cause decreased ankle joint plantarflexion at heel strike [6,10,13,23,28], reduced peak plantarflexion during loading response [6,13,23,28], and a delay in peak plantarflexion during loading response [6,10,13,28]. These reports however measured motion at the ankle using a rigid or segmental foot model and thus have been unable to measure the individual contributions of talocrural and subtalar motion to these changes. The talocrural kinematics of the current study agreed with these previous studies and showed wearing shoes significantly reduced plantarflexion at heel strike, reduced peak plantarflexion during loading response, and delayed peak plantarflexion during loading response at the talocrural joint (Fig. 2). The current work however was able to ascribe the trend of decreased plantarflexion during shod walking directly to motion of the talus relative to the tibia.

Subtalar joint kinematics have seldom been reported. Comparing barefoot to shod subtalar joint kinematics (Table 2), wearing shoes significantly decreased dorsiflexion at heel strike and peak dorsiflexion during loading response. This decreased subtalar joint dorsiflexion was sustained throughout stance phase. The only other study to directly measure subtalar joint motion during shod walking was done by Wang et al. in 2016 which used low-heeled (four cm) and high-heeled (10 cm) shoes [24]. This makes a direct comparison to the current study difficult. While the Wang study showed no significant plantar/dorsiflexion position differences comparing barefoot to low-heels, they did report significantly less dorsiflexed subtalar positions comparing barefoot to high-heels [24]. The clinical significance of a change of a few degrees remains to be established.

This analysis method allows the effect of how the talocrural and subtalar joints accommodate different footwear. The current study showed that wearing shoes resulted in changes to curve shape, beyond than just offsets. This can be seen by the difference in the shape of the talocrural joint curve in Fig. 2, with a 10.4° kinematic difference present in early stance but a much smaller difference at terminal stance. We expect this would vary based on factors such as the age of the population being studied, types of shoes worn, and activity level of

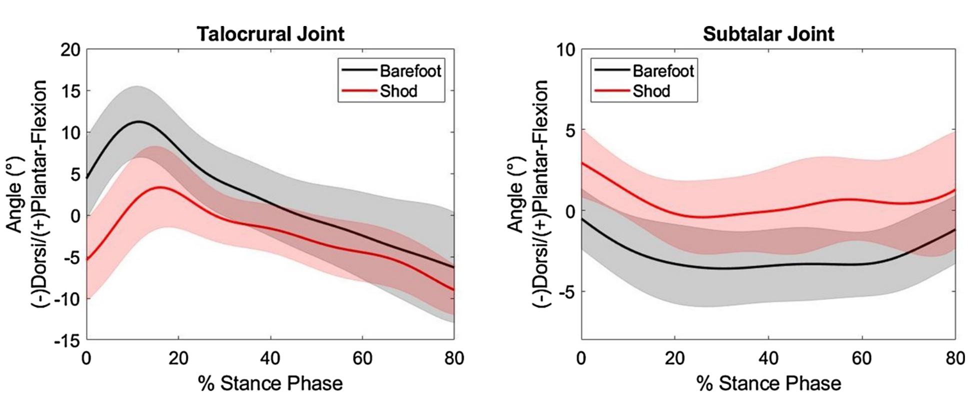

Fig. 2. Talocrural (left) and Subtalar (right) plantar/dorsiflexion angles during stance. The black solid line and grey band represents the mean and standard deviation of all thirteen subjects walking barefoot respectively. The red solid line and light red band represents the mean and standard deviation of all thirteen subjects walking in the athletic walking shoes respectively. Subject foot placement determined how much of stance phase could be analyzed for each trial collected. When the tibia vacated the fluoroscopic field of view during toe-off, the analysis stopped. For this reason, the kinematic analysis was limited to between heel strike and 80% stance (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 2
Kinematic and Temporal Spatial Statistics. Shod – Barefoot column indicates average of individual subject differences used in paired *t*-test.

				Statistical Analysis Data	
		Shod ($\bar{X}$ ± SD)	Barefoot ($\bar{X}$ ± SD)	Shod – Barefoot ($\bar{X}$ ± SD)	p value
KINEMATICS	Talocrural Position at Heel Strike	6.0° ± 5.3° DF	4.2° ± 4.8° PF	−10.4° ± 4.4°*	< 0.001
	Peak Talocrural Position	4.2° ± 4.7° PF	10.9° ± 4.3° PF	−6.8° ± 3.7°*	< 0.001
	Subtalar Position at Heel Strike	2.6° ± 2.4° PF	0.4° ± 1.4° DF	3.2° ± 3.1°*	0.01
	Peak Subtalar Position	1.5° ± 2.1° DF	3.5° ± 1.9° DF	2.5° ± 2.8°*	0.008
TEMPORAL	Cadence (steps/min)	95.3 ± 7.5	100.0 ± 7.5	−4.74 ± 3.64*	< 0.001
	Walking Speed (m/s)	1.12 ± 0.13	1.08 ± 0.17 m/s	0.04 ± 0.06 m/s*	0.03
	Stride Length (m)	1.4 ± 0.1 m	1.3 ± 0.1 m	0.10 ± 0.04 m*	< 0.001

* ($p < 0.05$), PF = plantarflexion, DF = dorsiflexion.

participants (easy walking vs long distance running).

While kinetics were not measured in the current study, a previous paper on shod gait by Kung et al. [13] showed that the increased ankle plantarflexion of shod gait also led to greater maximal dorsiflexor moment. In contrast, the barefoot condition induced greater energy generation by the ankle plantar flexors and invertors. Our talocrural joint kinematics showed the same trend of increased ankle plantarflexion during shod walking and we therefore would expect to see the same corresponding dorsiflexor moment as the previous results.

The kinematic coupling between the talocrural and subtalar joints is not well understood since most current methods are unable to directly measure talus motion. The current study showed a majority of the sagittal kinematic change from barefoot to shod gait occurred at the talocrural joint. This result can be intuitively expected as the talocrural joint is primarily responsible for sagittal plane motion of the ankle while coronal and transverse plane motion occur mainly at the subtalar joint. This was shown in the validation of this model which confirmed earlier cadaver work and gait studies using intercortical bone pins [25].

This work was limited in that it only used one shoe design and a small population of male subjects. It can be reasonably hypothesized that factors such as gender, age, and shoe types could yield different results. Also, the shoes in this study had a relatively high heel drop of 14 mm. Current walking and running shoe designs have a large variety of heel drop heights, posting, and other design variations. Future work such as the current study using dynamic fluoroscopy can explore the relationship between the motion of these two joints by varying these design parameters. Additionally, work by Hillstrom et al [29] has identified planus, rectus and cavus types of feet with a healthy population. However future work could explore the relationships between these foot types, various shoe design parameters, and talocrural and subtalar kinematics and elucidate important findings as to which combination of foot type and footwear most closely mimic physiologic motion.

There are several technical limitations to the current study. First is that the size of the image intensifier only allowed for 80% of stance to be captured as the tibia left the field of view during push-off. This was also a limitation in another fluoroscopy study of shod gait [23]. Larger image intensifiers would allow more of stance phase to be captured. The current study is also limited in that it used a single fluoroscope with a focused analysis on the sagittal plane [20]. Coronal and transverse plane motion are of interest during walking, running, and other athletic activities. To report on coronal or transverse motion individually, the fluoroscope could be repositioned relative to the walkway. A biplane fluoroscopic system would be required to report on simultaneous triaxial kinematics, and our group has recently published the technical details of such a system [30]. While a second fluoroscope would allow for the measurement of triaxial motion, this analysis also requires a CT scan which would increase radiation exposure and may not be necessary for all studies. While the dose was low, use of ionizing radiation was required for the current work. This estimated radiation exposure was ten μSv/trial, well below the United States Nuclear Regulatory Commission (USNRC) whole body annual occupational limits of five rems (50,000 μSv).

In conclusion, this work is the first to attribute the decrease in ankle plantarflexion of shod walking specifically to the talocrural joint when compared to barefoot walking. At the subtalar joint, shod walking showed an increase in plantarflexion throughout stance phase. The establishment of the feasibility of obtaining talocrural and subtalar kinematics presented in this paper will allow for future work to explore how they are impacted by variations in shoe designs, foot type, and other more complex motions. This could also help to better understand the kinematic coupling of the talocrural and their contributions to overall ankle joint motion.

Transparency document

The Transparency document associated with this article can be found in the online version.

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