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Abstract

Background: Identifying talar position during ambulation has proved difficult as the talus lacks palpable landmarks for skin marker placement and more invasive methodologies such as bone pins are not practical for most clinical subjects. A fluoroscopic motion system was used to track the talus and calcaneus, allowing kinematic analysis of the talocrural and subtalar joints.

Methods: Thirteen male subjects (mean age 22.9 ± 3.0 yr) previously screened for normal gait were tested. A fluoroscopy unit was used to collect images at 120 fps during stance. Sagittal motion of the talocrural and subtalar joints were analyzed.

Results: The inter-subject mean and standard deviation values for all 58 trials of 13 subjects are reported. Maximum talocrural joint plantarflexion of 11.2 degrees (4.3 degrees of standard deviation) occurred at 11% stance and maximum dorsiflexion of -6.9 degrees (5.6 degrees of standard deviation) occurred at 85%. Maximum subtalar joint plantarflexion of 4.8 degrees (1.0 degrees of standard deviation) occurred at 96% stance and maximum dorsiflexion of -3.6 degrees (2.3 degrees of standard deviation) occurred at 30%. Talocrural and subtalar range of motion values during stance were 18.1 and 8.4 degrees respectively.

Conclusion: Existing fluoroscopic technology is capable of defining sagittal plane talocrural and subtalar motion during gait. These kinematic results compare favorably with more invasive techniques. This type of assessment could support more routine analysis of *in vivo* bony motion during gait.

Clinical Relevance: Fluoroscopic technology offers improved sagittal plane motion evaluation during weightbearing with potential application in patients with end stage ankle arthritis, postoperative ankle replacements and fusions, and orthotics and braces.

Keywords: gait analysis; hindfoot, subtalar joint, talocrural joint; ankle joint; biomechanics; weightbearing; fluoroscopy; sagittal motion

Introduction

Gait analysis is a proven method used to study lower extremity and foot and ankle kinematics.[8, 17, 19, 21, 22, 25] The development of this technology has allowed us to evaluate several foot and ankle conditions and also compare treatments and postoperative outcomes.[4, 5, 7, 16, 31]

One limitation of current foot and ankle gait analysis models is their inability to uncouple talocrural and subtalar joint motion. These models use skin mounted markers attached to palpable bony landmarks to define the lower leg as one segment and the hindfoot as the adjacent segment. Hindfoot markers are usually only placed on the calcaneus. This is done to avoid interference with underlying tissue, to reduce skin motion artifact, and because the talus lacks palpable

landmarks for accurate, consistent marker placement.[25] Treating the talocrural and subtalar joint complex as one articulation does not allow for a true biomechanical analysis of either joint. This combining of motions only permits quantification of the summation of their individual contributions.

The ability to measure motion individually in these joints would allow us to further orthopedic knowledge in numerous areas. Such information would complement multiple recent studies reporting outcomes and ranges of motion.[3, 6, 9, 11, 27-29, 35] A better understanding of individual and composite joint contributions to hindfoot motion during ambulation could improve treatment strategies. This includes kinematic effects of ankle arthritis and subsequent treatments, both operative and non-operative. Other applications include evaluation of joint motion resulting from pes planovalgus, tarsal coalition and instability. The quantitative effects following arthrodesis, arthroplasty, arthroscopy and open reduction internal fixation of the calcaneus, talus, pilon and malleolar fractures could be described. Further improvements could be anticipated when prescribing orthotics and shoe modifications for specific foot and ankle conditions.

An important consideration when obtaining joint motion data is the need to evaluate the activity of interest. Non-weight bearing studies of foot and ankle motion, for instance, do not provide an accurate assessment of weightbearing responses to load during gait. Weightbearing has been shown to alter measured joint ranges. Loading the ankle joint demonstrates increased sagittal motion. As shown by Lindsjo et al., there is a threefold increase in dorsiflexion when subjects were standing and weightbearing (32.5±6.9) compared to supine with knees straight (9.8±5.7) or flexed (14.0±6.0). They also demonstrated a slight increase in plantarflexion of loaded ankles (44.7±7.6) compared to supine with knees straight (37.6±6.6) or flexed (41.8±6.8).[23]

Bone pin based multi-segmental foot models are capable of individually measuring ankle and subtalar motion during weightbearing activities. Insertion of intra-cortical pins requires the assistance of an experienced orthopaedic surgeon and must be done under sterile operating conditions, and local anesthesia is used. After pin removal, subjects are given antibiotics and/or pain medication. While none of these studies report clinical complications, they all report subject pain and/or walking with a limp up to one week post analysis.[1, 2, 24, 33] To date, bone pin methodologies have been limited to research on healthy adult subjects.

Fluoroscopic imaging offers another method for tracking the ankle and subtalar joints. The dynamic radiographic method allows for the collection of images during motion. One of the first pioneering studies using fluoroscopy to track foot motion was done by Green et al. in 1975.[14] Fluoroscopic images were captured on 16 mm film and anatomic bony motion (non-quantitative) was described as

subjects moved their foot from maximal pronation to maximal supination. Since the work of green, a number of studies applying fluoroscopic techniques to the foot and ankle appear in the literature. In 2005, Wearing et al. used single plane fluoroscopy and static positioning to determine errors in measuring sagittal arch kinematics of the human foot using dried bone pieces.[32] In 2007, Wrbaskic and Dowling used single plane fluoroscopic imaging (60 Hz.) to report on the deformable characteristics of the human foot, but did not include kinematic results.[34] In a 2011 study, Shultz et al. quantified skin motion artifact error of the foot using single plane fluoroscopy and quasi-static foot positioning.[30] In one of the most recent studies, Iaquinto et al. tracked the dynamic motion of beads embedded in plastic at known locations to validate a biplane fluoroscopy system for quantifying foot kinematics.[18] Two articles in the literature use fluoroscopy to report ankle joint kinematics, but both use static positioning of the foot. In a 2000 study by Komistek et al., sagittal plane ankle kinematics were reported for ten subjects between static dorsiflexion and static plantarflexion positions.[20] Because of the static nature of the study methodology, only ranges of motion could be reported. In a bi-planar (dual-orthogonal fluoroscopy) study by de Asla et al., talocrural, subtalar, and tibiocaneal (calcaneus with respect to tibia) kinematics were reported among three static positions (heel strike, mid-stance, and toe-off).[10] Similar to the Komistek et al. study, static positioning of the foot limited the results to ranges of motion.

The goal of this study was to apply a fluoroscopic motion analysis system to assess talocrural and subtalar joint motion in the sagittal plane during the stance phase of gait.

Materials and Methods

In this Institutional Review Board (IRB) approved study, 13 male subjects (mean age 22.9 ± 3.0 yr, mean weight 77.2 ± 6.9 kg, mean height 178.2 ± 3.7 cm), previously screened for exclusion criteria were tested over a four month period. Exclusion criteria included any significant injury to the foot and/or ankle or any previous lower extremity surgery (bilateral).

A standard fluoroscopic system was synchronized with an existing Vicon, Nexus motion analysis system (Vicon Motion Systems, Inc., Oxford, UK). The fluoroscopy unit (OEC 9000, GE, Fairfield, CT) was modified so that the emitter and image intensifier (II) were detached and mounted on opposite sides of the width of the walkway (Figure 1).

The right leg and foot of each subject were instrumented with six reflective markers (d = 16 mm) in accordance with the distal portion of the Plug-In-Gait model and an additional marker (Table 1). Simultaneous motion analysis and fluoroscopic data were collected (120 fps) as subjects walked at a self-selected

pace along the eight meter custom walkway. The fluoroscopic system was manually activated at heel strike/initial contact and de-activated just after toe-off. During fluoroscopic data collection radiation levels were set from 90-110 kVp, and 0.5-1.7 mA depending on patient-specific image quality analyses. These radiation levels were confirmed by the radiation safety department prior to application. Each subject completed five barefoot trials with fluoroscopic imaging as approved by the IRB. Due to foot misplacements within the capture volume during radiation exposure, seven of the 13 subjects had four acceptable trials. Following dynamic data collection, subjects were escorted to a nearby x-ray suite where a single limb support barefoot x-ray was taken of their right foot placed at the same foot progression angle observed during foot flat of the dynamic image collection.

The fluoroscopic system was used to analyze the talocrural and subtalar joint motion. This required tracking of tibial, talar and calcaneal position during stance. The talus and calcaneus were tracked directly in each of the collected fluoroscopic images. Two points of interest per bone (Figure 2) were translated from pixel coordinates to motion analysis global coordinates using the known external marker (Table 1) location data. 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. 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. Although only talocrural and subtalar motion is reported in the current study, the external marked based model is able to track motion proximal to the ankle.[12, 13] Kinematic analysis was completed by using the International Society of Biomechanics (ISB) recommended Joint Coordinate Method, with motion being reported as distal segment movement with respect to proximal.[15] This kinematic model was additionally applied to the static lateral x-ray which defined neutral position. Kinematic results are reported relative to this neutral position.

Results

The talocrural joint increases to maximum plantarflexion during loading response followed by dorsiflexion motion during mid and terminal stance (Figure 3). Maximum talocrural dorsiflexion occurs at the beginning of preswing followed by plantarflexion towards swing phase. The subtalar joint is in a neutral position at heel strike followed by dorsiflexion into mid-stance. Maximum subtalar dorsiflexion occurs during mid-stance, though little motion occurs again until the middle of terminal stance at which point plantarflexion occurs for the rest of stance. The maximum talocrural plantar and dorsiflexion kinematics occur at 11% and 85% stance respectively (Table 2). The maximum subtalar plantar and dorsiflexion kinematics occur greater than 96% and 30% stance respectively.

Discussion

Existing technology that allows evaluation of sagittal talocrural and subtalar motion supports a better understanding of *in vivo* joint kinematics. Brodsky et al used the Milwaukee Foot Model[19] to evaluate the hindfoot motion of 46 patients following total ankle arthroplasty with a STAR prosthesis. This study found decreased hindfoot motion in patients following ankle arthroplasty in both the sagittal and coronal planes. The authors highlighted the need to better understand hindfoot and more specifically subtalar joint pathology present both before and after surgery. They questioned whether subtalar arthritis existed prior to surgery as a result of the end stage ankle arthritis and subsequent gait abnormalities, or if it developed following the ankle arthroplasty.[6]

The only current foot model that reports talocrural and subtalar motion during gait uses direct measurement methods with implanted bone pins. Kinematic results from this methodology compare favorably with the current fluoroscopic model, both in morphology and range of motion. Fluoroscopic maximum talocrural plantar and dorsiflexion kinematics occur at 11% and 85% stance respectively, with a range of motion of 18.1 degrees (Figure 3, Table 2). Sagittal plane talocrural joint kinematic graphs from two recent bone pin studies agree with these results, showing maximum plantarflexion occurring before 15% of stance, and maximum dorsiflexion occurring after 80% with range of motion values between 11.3 and 18.7 degrees.[1, 24] Fluoroscopic maximum talocrural plantar and dorsiflexion kinematics occur at the end of preswing and 30% stance respectively, with a range of motion of 8.4 degrees (Figure 3, Table 2). The aforementioned bone pin studies show varied ranges of maximum plantar and dorsiflexion, but correspond to a range of motion between 2.8 and 8.8 degrees.[1, 24]

Current external marker based multi-segmental foot models report only hindfoot/calcaneal segment motion with respect to a lower leg segment.[8, 17, 19, 21, 22] Results from these models cannot be directly compared to the current fluoroscopic results because of their inability to differentiate between talocrural and subtalar motion. The 2008 bone pin study, however, does report calcaneal motion with respect to tibia and can be directly compared to the external marker based models. In Lundgren's bone pin study the average tibial-calcaneal sagittal plane ROM is 17 degrees for six subjects.[24] The aforementioned external marker based models report an average of 18 degrees of sagittal plane hindfoot/calcaneal segment motion on a total of 39 feet.[8, 17, 19, 21, 22] While the fluoroscopic model does not directly measure calcaneal motion with respect to tibia, the talocrural and subtalar motion does compare favorably to the 2008 bone pin study.

Current study limitations include a narrow sample of adult male subjects aged 18 to 28 with no reported gait deficiencies or prior bony foot injury. While the

results of this pilot study are promising, further studies should be conducted using a larger cohort of healthy as well as pathologic gait populations. The current study is also limited to a single plane (sagittal) analysis of hindfoot motion components. A further limitation is the use of ionizing radiation with current levels estimated at ten μSv/trial. United States Nuclear Regulatory Commission (USNRC) whole body annual occupational limits are five rems (50,000 μSv).

In conclusion, sagittal fluoroscopic imaging compares favorably to results from bone pin implants without the need for invasive procedures. With regard to motion contribution, both talocrural and subtalar joints exhibit sagittal motion throughout stance. Continued assessment of talocrural and subtalar ranges of motion during stance may further our understanding of hindfoot biomechanics during gait with implications for improved clinical applications. These clinical applications include evaluation of joint motion in pathologic conditions such as arthritis, pes planovalgus, tarsal coalition, and instability. The postoperative motion of the ankle and subtalar joints may be investigated following arthrodesis, arthroplasty, arthroscopy, and open reduction internal fixation of calcaneus, talus, pilon, and ankle fractures. Nonoperative treatment of foot and ankle conditions with custom fabricated orthoses and shoe modifications may also benefit from the development of this system. Further applications would include higher speed analyses of running kinematics and footwear choices among recreational to elite athletes.

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TABLES

Table 1: External marker locations.

Marker Location	Marker Name
Calcaneal tuberosity	M1
Head of the 2nd metatarsal	M2
Medial malleolus	M3
Lateral malleolus	M4
Medial femoral epicondyle	M5
Lateral femoral epicondyle	M6

Table 2: Talocrural and subtalar kinematics during stance phase.

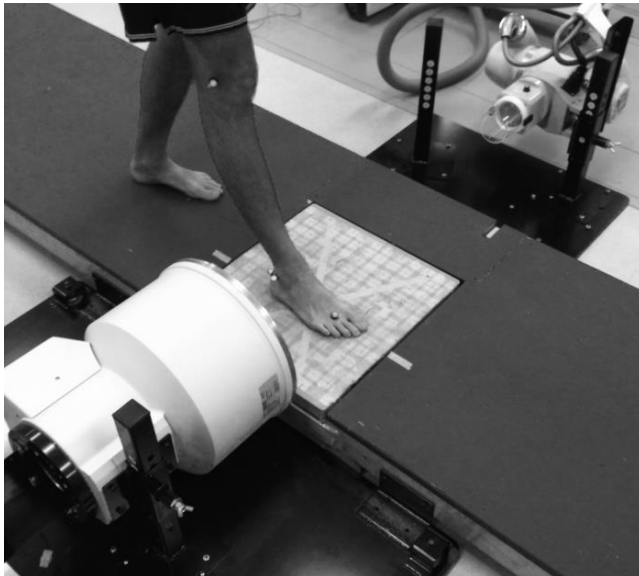|	Talocrural Joint		Subtalar Joint	
	Degrees	% Stance Phase	Degrees	% Stance
Max Plantarflexion [SD]	11.2°	11%	4.8°	96%
Max Dorsiflexion [SD]	-6.9° [5.6°]	85%	-3.6° [2.3°]	30%

Figures

Figure 1. System configuration showing the walkway, emitter (farside), and image intensifier (nearside). Also shown is typical foot placement during image collection.
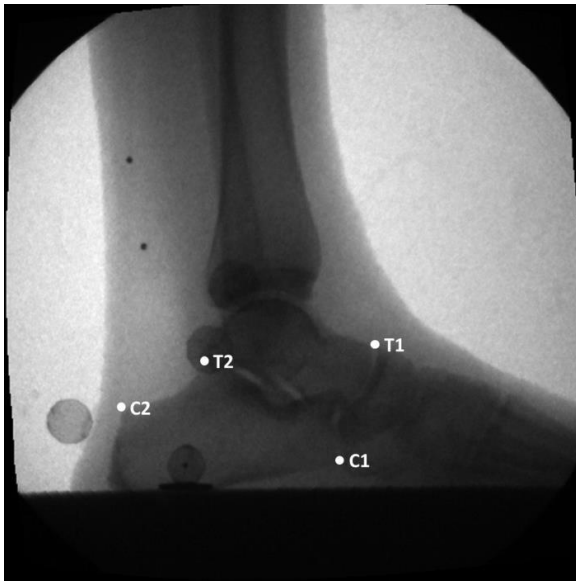
Figure 2. Typical fluoroscopic image showing the points of interested used to fluoroscopically track the talus and calcaneus (Talus: T1 – superior border of the talonavicular joint, T2 – posterior talar process; Calcaneus: C1 – inferior aspect of the calcaneocuboid joint, C2 – superior aspect of the posterior tuberosity of the calcaneus).
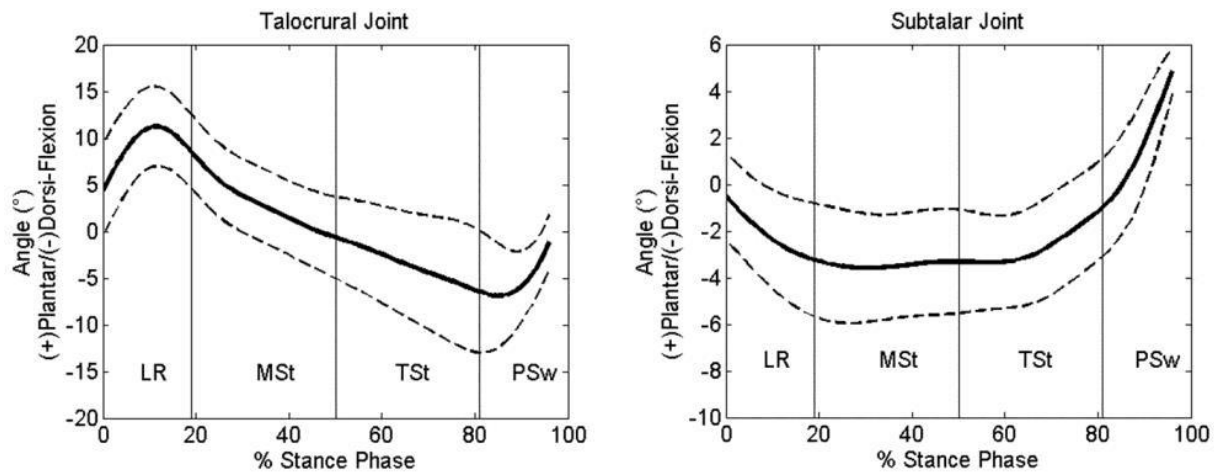

Figure 3. Talocrural (left) and Subtalar (right) plantar/dorsiflexion angles. Solid lines represent mean of all 13 subject trials. Dashed lines represent mean ± 1 SD. Results are sub-divided into LR: loading response (initial contact through contralateral toe-off) , MSt: mid-stance (contralateral toe-off through ipsilateral heel-rise), TSt: terminal stance (ipsilateral heel-rise through contralateral initial contact), and PSw: preswing (contralateral initial contact through ipsilateral toe-off).[26] Missing data between 97-100% of stance corresponds to the foot vacating the field of view.