Koren E. Roach

Department of Orthopaedics,
University of Utah,
590 Wakara Way,
Salt Lake City, UT 84108;
Department of Bioengineering,
University of Utah,
36 S. Wasatch Drive, Room 3100,
Salt Lake City, UT 84112
e-mail: Koren.Roach@utah.edu

Bibo Wang

Department of Orthopaedics,
University of Utah,
590 Wakara Way,
Salt Lake City, UT 84108;
Department of Orthopaedics,
Shanghai Ruijin Hospital,
Shanghai Jiao Tong University
School of Medicine,
Shanghai 200025, China
e-mail: bibo_wang@outlook.com

Ashley L. Kapron

Department of Orthopaedics,
University of Utah,
590 Wakara Way,
Salt Lake City, UT 84108;
Department of Bioengineering,
University of Utah,
36 S. Wasatch Drive, Room 3100,
Salt Lake City, UT 84112;
Scientific Computing and Imaging Institute,
72 S Central Campus Drive, Room 3750,
Salt Lake City, UT 84112
e-mail: Ashley.Kapron@utah.edu

Niccolo M. Fiorentino

Mem. ASME
Department of Orthopaedics,
University of Utah,
590 Wakara Way,
Salt Lake City, UT 84108
e-mail: niccolo.fiorentino@utah.edu

Charles L. Saltzman

Department of Orthopaedics,
University of Utah,
590 Wakara Way,
Salt Lake City, UT 84108
e-mail: Charles.Saltzman@hsc.utah.edu

K. Bo Foreman

Department of Orthopaedics,
University of Utah,
590 Wakara Way,
Salt Lake City, UT 84108;
Department of Physical Therapy,
University of Utah,
520 Wakara Way, Suite 240,
Salt Lake City, UT 84108
e-mail: bo.foreman@hsc.utah.edu

In Vivo Kinematics of the Tibiotalar and Subtalar Joints in Asymptomatic Subjects: A High-Speed Dual Fluoroscopy Study

Measurements of joint kinematics are essential to understand the pathomechanics of ankle disease and the effects of treatment. Traditional motion capture techniques do not provide measurements of independent tibiotalar and subtalar joint motion. In this study, high-speed dual fluoroscopy images of ten asymptomatic adults were acquired during treadmill walking at 0.5 m/s and 1.0 m/s and a single-leg, balanced heel-rise. Three-dimensional (3D) CT models of each bone and dual fluoroscopy images were used to quantify in vivo kinematics for the tibiotalar and subtalar joints. Dynamic tibiotalar and subtalar mean joint angles often exhibited opposing trends during captured stance. During both speeds of walking, the tibiotalar joint had significantly greater dorsiflexion (D/P) angular ROM than the subtalar joint while the subtalar joint demonstrated greater inversion/eversion (In/Ev) and internal/external rotation (IR/ER) than the tibiotalar joint. During balanced heel-rise, only D/P and In/Ev were significantly different between the tibiotalar and subtalar joints. Translational ROM in the anterior/posterior (AP) direction was significantly greater in the subtalar than the tibiotalar joint during walking at 0.5 m/s. Overall, our results support the long-held belief that the tibiotalar joint is primarily responsible for D/P, while the subtalar joint facilitates In/Ev and IR/ER. However, the subtalar joint provided considerable D/P rotation, and the tibiotalar joint rotated about all three axes, which, along with translational motion, suggests that each joint undergoes complex, 3D motion. [DOI: 10.1115/1.4034263]

¹Corresponding author.

Manuscript received January 12, 2016; final manuscript received July 14, 2016;
published online August 4, 2016. Assoc. Editor: Paul Rullkoetter.

Andrew E. Anderson¹

Mem. ASME

Department of Orthopaedics,

University of Utah,

590 Wakara Way,

Salt Lake City, UT 84108;

Department of Bioengineering,

University of Utah,

36 S. Wasatch Drive, Room 3100,

Salt Lake City, UT 84112;

Scientific Computing and Imaging Institute,

72 S Central Campus Drive, Room 3750,

Salt Lake City, UT 84112;

Department of Physical Therapy,

University of Utah,

520 Wakara Way, Suite 240,

Salt Lake City, UT 84108

e-mail: Andrew.Anderson@hsc.utah.edu

1 Introduction

The tibiotalar and subtalar joints play important roles in guiding articulation of the hindfoot. Deleterious joint angles and translations (i.e., kinematics) at the hindfoot may contribute to the development of osteoarthritis [1]. Accordingly, measurements of tibiotalar and subtalar kinematics could identify mechanisms in which OA progresses in the hindfoot.

Traditionally, the tibiotalar joint is thought to facilitate rotation in the dorsi/plantarflexion (D/P) direction [2–6], while the subtalar joint is believed to coordinate inversion/eversion (In/Ev) [2,3]. However, additional studies in the literature suggest that the subtalar joint offers more complex motion, including internal/external rotation (IR/ER) [4,5,7–9]. Further studies have claimed that ankle motion can be attributed to tibiotalar [10,11] or subtalar [12,13] axes of rotation that have different locations and orientations depending on the motion involved.

The lack of consensus regarding articulation of the tibiotalar and subtalar joints may be partially explained by limitations in the technology used to measure hindfoot motion. Specifically, the most common method to measure kinematics uses reflective skin markers (e.g., see Ref. [14]), but there are several drawbacks with this approach, including errors caused by variability in the placement of markers, artifact from motion of the skin markers relative to the bone, and inaccuracies in the estimation of joint center [15–17]. Another limitation is that kinematics calculated by skin marker motion analysis are visualized with respect to a generically scaled model, and thus, the relationship between individual anatomical features and the ensuing joint motion cannot be discerned. Finally, in the absence of a location to place a skin marker about the talus, standard motion analysis cannot measure motion of the tibiotalar joint independent from the subtalar joint. Thus, most gait studies report hindfoot motion as that of the tibia relative to the calcaneus.

To circumvent the limitations of standard motion capture, investigators have used dual fluoroscopy to measure three-dimensional (3D) joint kinematics in vivo. Using dual fluoroscopy, two X-ray images are aligned with digitally reconstructed radiographs created from volumetric computed tomography (CT) or magnetic resonance scans. In addition to having submillimeter and subdegree accuracy, dual fluoroscopy enables visualization of kinematics relative to subject-specific reconstructions of bony anatomy. A handful of dual fluoroscopy studies of the hindfoot have been reported to date. However, many of these only investigated quasi-static motion, which neglects inertial effects [18–20]. Three studies have used dual fluoroscopy to quantify hindfoot kinematics during dynamic activities [21–23], but they only measured tibio-calcaneal motion [21], or did not report joint translations [21–23].

To serve as baseline data for the study of patients with ankle OA, the objective of this study was to use dual fluoroscopy to quantify in vivo kinematics of the tibiotalar and subtalar joints during activities of daily living in asymptomatic, nonpathologic controls. Given early, canonical descriptions of hindfoot motion, we hypothesized that D/P of the tibiotalar joint would be larger than that at the subtalar joint. We also hypothesized that subtalar In/Ev and IR/ER would be larger than that observed at the tibiotalar joint.

2 Methods

2.1 Subject Recruitment and Screening. Following approval of the institutional ethics board and informed consent (IRB#65620), ten healthy volunteers (five male, five female; age: 30.9 ± 7.2 yrs, BMI: 23.5 ± 3.5) without a history of foot or ankle pain or pathology or back or lower limb surgery were enrolled in this study. Radiographs were acquired of both feet in the lateral, anterior–posterior (AP), hindfoot, and dorsal–plantar views. Radiographs were screened to eliminate varus/valgus deformities, osteophytes, and OA in either ankle as assessed by Kellgren–Lawrence grades > 1 . Subjects were also screened for pes planus or cavus feet. None of the ten subjects were excluded based on these criteria.

2.2 Dual Fluoroscopy, Skin Marker Motion Capture. A dual fluoroscopy system that was previously shown to exhibit a mean rotational and translational bias of 0.25 ± 0.81 deg and 0.03 ± 0.35 mm, respectively, measured tibiotalar and subtalar kinematics [24]. The dual fluoroscopy system was temporally and spatially aligned with a ten-camera near-infrared motion analysis system (Vicon Motion Systems, Oxford, UK). The dual fluoroscopy and motion capture systems were synced temporally using an external trigger and spatially using a custom calibration cube [25]. The system was positioned around a dual-belt instrumented treadmill (Bertec Corp., Columbus, OH) such that each emitter and intensifier was approximately 110 cm from one another. The angle between the two faces of the image intensifiers was approximately 90 deg [24]. A modified Helen-Hayes configuration of reflective skin markers was applied to each subject to enable 3D positional tracking of the pelvis and bilateral thighs, shank, and feet [26]. Subjects performed a single-leg, balanced heel-rise and walked on the treadmill at 0.5 m/s and 1.0 m/s. Walking was selected as it is a common activity of daily living. The two walking speeds were chosen to facilitate comparison to patients in the future, in anticipation that pathologic groups may not be able to walk at speeds greater than 1.0 m/s. The balanced heel-rise activity was chosen because it was likely to require careful

coordination and a large amount of plantarflexion. For treadmill walking, subjects ambulated for at least 30 s prior to capture and were not notified when dual fluoroscopy acquisition would begin. The balanced heel-rise activity was practiced prior to motion capture. Subjects were barefoot for all activities.

Motion data were acquired for six right ankles and four left ankles. Trajectories of skin markers were captured at 300 Hz. The emitter beam energy settings for the ten subjects ranged from 62 kVp to 78 kVp and from 1.4 mAs to 2.2 mAs [24]. Dual fluoroscopy images were acquired at 300 Hz with 1500 μ s of camera exposure for both walking and balanced heel-rise activities [24]. The entire balanced heel-rise activity was imaged as the tibia, talus, and calcaneus never exited the combined field of view of the dual fluoroscopy system. For treadmill walking, the heelstrike and toe-off portions of the gait cycle were imaged as separate trials as the foot moved out of the dual fluoroscopy field of view prior to the completion of stance. Combined, the portion of gait imaged from the separate trials of heelstrike and toe-off activities were referred to as “captured stance.” Dual fluoroscopy and skin marker data were acquired for two trials of heelstrike, toe-off, and balanced heel-rise. Total fluoroscopy time for each subject did not exceed 60 s.

2.3 Computed Tomography, Model-Based Markerless Tracking. A computed tomography (CT) scan was acquired of each volunteer (SOMATOM Definition AS, Siemens Medical Solutions, Malvern, PA) from midtibia through their toe-tips at 1.0 mm slice thickness, 366 ± 65.2 mm field of view, 512×512 acquisition matrix, 100 kV, 16–73 mAs [24]. The CT images were segmented (Amira 5.5, Visage Imaging, San Diego, CA) to generate 3D surface reconstructions of each bone [24]. Positions of the tibia, talus, and calcaneus were determined semi-automatically using model-based markerless tracking [27]. Total radiation exposure for each subject, including both CT and dual fluoroscopy imaging, did not exceed 10 days of background radiation or 0.11 mSv.

2.4 Calculation of Dynamic Kinematics, Range of Motion (ROM). A landmark-based approach defined coordinate systems for the tibia, talus, and calcaneus [24]. To establish a weight-bearing neutral position, all three bones were aligned to their respective midstance positions as determined by dual fluoroscopy. Next, the talus and calcaneus coordinate systems were aligned with the tibia coordinate system and offset to the origin of each bone’s anatomical coordinate system. Skin marker data were used to determine the time points for heelstrike, midstance, and toe-off events during the walking trials analyzed by dual fluoroscopy. The frame corresponding to heelstrike was defined by the minimum height position of the heel-marker following a downward trajectory. Similarly, the frame corresponding to toe-off was defined as the minimum height position of the toe-marker prior to its upward trajectory. The midpoint frame between heelstrike and toe-off was used as midstance. The time between heelstrike and toe-off (as determined by the skin marker data) was used to normalize each trial to the stance phase of the gait cycle. Gait trials were aligned at either heelstrike (0% of normalized stance) or toe-off (100% of normalized stance). Inflection points from D/P angles calculated between the tibia and calcaneus were used to normalize the balanced heel-rise activity across subjects. The five inflection points used were: maximum dorsiflexion at the beginning and end of each trial (two points), maximum plantarflexion midtrial (one point), and the second derivative zero-crossings of the D/P angles between the tibia and calcaneus (two points).

Dynamic joint angles and translations were calculated for the tibiotalar and subtalar joints as described previously [24]. Dynamic joint angles and translations were smoothed with a fourth-order bidirectional low-pass Butterworth filter. A residual analysis method was used to select a cutoff frequency of 10 Hz [28]. Joint angles were reported for D/P, In/Ev, and IR/ER, where dorsiflexion, eversion, and external rotation were considered positive. Joint translations were reported in the medial–lateral (ML),

anterior–posterior (AP), and superior–inferior (SI) directions. Joint angles and translations were calculated in terms of the more distal bone, with respect to the more proximal bone (e.g., the talus with respect to the tibia). A total of 9 out of 80 gait trials were excluded from the analysis as the event of interest (heelstrike or toe-off) occurred outside the fluoroscopic field of view. One subject had only one balanced heel-rise trial; limitations imposed on total fluoroscopy time prohibited acquisition of additional trials.

Range of motion (ROM) was determined for rotation about, and translation along, each anatomical axis for the balanced heel-rise activity and captured stance for each walking speed. The minimum and maximum joint angles and translations were determined from all frames acquired between heelstrike and toe-off events from all available trials. Similarly, for the balanced heel-rise activity, minimum and maximum joint angles and translations were determined from all available frames and trials of each subject. ROM was determined by calculating the absolute value of the minimum value subtracted from the maximum value.

2.5 Data and Statistical Analysis. The mean and 95% confidence interval (CI) were determined for all rotations per normalized stance across all subjects and for each activity. Due to the nature of the dynamic data capture, not all walking trials started and ended at the same percentage of normalized stance. As such, the mean and 95% CI at a particular percentage of the stance phase were based on the number of data points available, similar to a moving average. Here, we calculated the mean and 95% CI for all points between heelstrike and toe-off for which there were data available for at least five subjects. For the balanced heel-rise activity, the mean and 95% CI were calculated over the normalized event for all subjects and available trials.

The mean and 95% CI were calculated across all subjects for the ROM of each joint, activity, and rotation or translation. A paired *t*-test was used to determine if rotational and translational ROM during an activity were statistically significantly different between the tibiotalar and subtalar joints.

3 Results

3.1 Dynamic Kinematics. The dynamic joint angles of the individual subjects and trials appeared to follow a similar trend (Fig. 1). This statement was also true for the individual balanced heel-rise trials (data not shown). However, there was considerable variation in the individual joint angles, especially with regard to tibiotalar D/P and IR/ER angles. Here, there was a noticeable offset in the magnitude of the joint angles between subjects.

During gait, the tibiotalar and subtalar joint angles often demonstrated similar trends, which were visible on the individual plots (Fig. 1) and averaged data (Fig. 2). For example, at 0.5 m/s, the mean D/P angles of both the tibiotalar and subtalar joints increased between 8% and 17% of stance (Fig. 2). Similarly, at 1.0 m/s, the mean D/P angles of both joints increased between 10% and 19% of stance (Fig. 2). Additionally, the mean D/P angles of the tibiotalar and subtalar joints showed a general increase in plantarflexion (negative dorsiflexion) prior to toe-off, between 77% and 100% of stance at 0.5 m/s, and a similar increase in plantarflexion between 85% and 100% of stance at 1.0 m/s (Fig. 2).

Several measures of joint angles during gait also demonstrated opposing motions between the two joints. For example, during walking at 0.5 m/s, the mean In/Ev angles increased 2.2 deg at the tibiotalar joint and decreased 9.4 deg at the subtalar joint between 78% and 100% of stance (Fig. 2). Similar trends were observed during walking at 1.0 m/s, where mean In/Ev angles increased 1.8 deg at the tibiotalar joint and decreased 8.9 deg at the subtalar joint between 77% and 98% of stance (Fig. 2). As another example, at both 0.5 m/s and 1.0 m/s, mean D/P angles decreased (6.8 deg and 9.1 deg, respectively) for the tibiotalar joint and increased (1.2 deg and 1.9 deg, respectively) for the subtalar joint between heelstrike and approximately 9% of stance (Fig. 2).

Fig. 1 Tibiotalar (left) and subtalar (right) dynamic joint angles for the individual subjects during captured stance at 1.0 m/s. Dorsi- (+)/plantarflexion (top), inversion/eversion (+) (middle), and internal/external (+) rotation (bottom) were plotted per normalized stance phase with all subjects aligned at heelstrike (0%) and toe-off (100%) for heelstrike and toe-off trials, respectively. Each solid line depicts one representative trial for heelstrike and toe-off trials, respectively. Note: separate trials were collected for the heelstrike and toe-off portions of stance as the foot exited the field of view of the fluoroscopes prior to the completion of the entire stance phase. Missing data reflect the portion of stance that was not imaged.

During balanced heel-rise, several rotational measures demonstrated a trend convex in shape, most prominently the mean tibiotalar D/P angles (Fig. 3). Between the start and the peak of the balanced heel-rise activity (approximately 50% of balanced heel-rise), mean tibiotalar D/P angles decreased from 8.4 deg to -20.1 deg, while mean subtalar D/P angles decreased from 0.6 deg to -3.2 deg. Mean tibiotalar and subtalar IR/ER angles and subtalar In/Ev angles also exhibited trends that were slightly convex in shape over the course of normalized balanced heel-rise. These results indicate that the subtalar joint transitioned from a neutral position to a slightly inverted and internally rotated position at the peak of the balanced heel-rise and back to a neutral position.

3.2 Range of Motion. During captured stance and heel-rise, mean D/P ROM of the tibiotalar joint was significantly larger than that of the subtalar joint (all $p < 0.01$) (Fig. 4). Conversely, mean In/Ev of the subtalar joint was significantly larger than that of the tibiotalar joint (all $p < 0.001$). Mean IR/ER of the subtalar joint was significantly larger than that of the tibiotalar joint during captured stance (all $p < 0.01$), but not during balanced heel-rise ($p = 0.59$).

Significant differences between the tibiotalar and subtalar joints were less apparent for translational ROM (Fig. 4). During captured stance at 0.5 m/s, the mean subtalar translational ROM in the AP direction was significantly larger than that of the tibiotalar

Fig. 2 Tibiotalar and subtalar mean joint angles during captured stance at 0.5 m/s (left) and 1.0 m/s (right). Dorsi- (+)/plantarflexion (top), inversion/eversion (+) (middle), and internal/external (+) rotation (bottom). Solid line = mean. Shaded areas = 95% confidence intervals. Plotted per normalized stance. Note: separate trials were collected for the heelstrike and toe-off portions of stance as the foot exited the field of view of the fluoroscopes prior to the completion of the entire stance phase. Missing data reflect the portion of stance that was not imaged.

joint ($p < 0.01$). No other significant differences in translational ROM between the two joints were found.

4 Discussion

In this study, we quantified in vivo dynamic kinematics of the tibiotalar and subtalar joints in nonpathologic controls during two treadmill walking speeds and a single-leg, balanced heel-rise. We also quantified and compared total angular and translational ROM. Overall, we found that the tibiotalar joint contributed to the majority of D/P movement of the hindfoot, while the subtalar joint was primarily responsible for In/Ev and IR/ER motion. These results confirmed various long-held hypotheses regarding the mode of action for these joints, specifically, that the tibiotalar joint contributes mainly to D/P motion [2,3,5,6,11], while the subtalar

joint primarily contributes to In/EV motion [2,3,6] along with IR/ER [4,5,7–9]. Nevertheless, both joints provided considerable rotation and translation about all three axes, a concept that has been postulated by others [29–31], but not analyzed in vivo during the activities included herein. The subtalar joint, in particular, experienced substantial D/P and notable translational motion. Our findings are important, as they suggest that assuming less than six degrees-of-freedom for either joint may be an oversimplification that could lead to erroneous estimates of biomechanical measures at the foot/ankle, or proximal along the kinematic chain.

Individual dynamic joint angles during captured stance and balanced heel-rise indicated that there was considerable variation in ankle motion, even among asymptomatic subjects screened for ankle pathology. Individual trials displayed similar trends in dynamic joint angles despite the intersubject variation. This intersubject variation

Fig. 3 Tibiotalar and subtalar mean joint angles during single-leg balanced heel-rise. Dorsi- (+)/plantarflexion (top), inversion/eversion (+) (middle), and internal/external (+) rotation (bottom). Solid line = mean. Shaded areas = 95% confidence intervals. Plotted per normalized heel-rise.

may arise due to bone morphology and its effects on the orientation of anatomical coordinate systems or subject-specific muscle activation. Aside from variations across subjects, some individual dynamic joint angles exhibited fluctuations, primarily during In/Ev

and IR/ER. Such fluctuations may indicate that In/Ev and IR/ER are stabilizing mechanisms that compensate for varying load distributions during walking. Individual dynamic joint angles during gait appeared to have smaller fluctuations than balanced heel-rise, possibly as a result of the different loading paradigms. According to Stormont et al., when loaded, the articular surface of the ankle joint is important for modulation of IR/ER, along with several ligaments [32]. However, Stormont et al. postulated that the articular surface is the only mechanism able to restrict In/Ev movement [32]. The fluctuation in both In/Ev and IR/ER observed in our study may indicate that both ligaments and the articular surface promote general ankle stability.

Evaluation of mean dynamic joint angles demonstrated that the tibiotalar and subtalar joints often exhibited opposing trends. However, this was not uniformly consistent between gait and balanced heel-rise activities. This may be the result of different loading schemes, independent talus movement, or the rotation of the tibia and calcaneus in opposite directions. Despite these opposing trends, motions were not exclusive to the tibiotalar or subtalar joints. Although one joint was frequently a primary contributor to a rotational ROM metric, the other provided considerable secondary rotational motion.

Subtalar translational ROM was significantly greater than that of the tibiotalar joint in the AP direction, which may result from the unconfined articular geometry in this direction. In particular, the talus moved away from the calcaneus during stance, as the talus moved from a closed-packed position in dorsiflexion to a more open configuration during plantarflexion. Conversely, the talus would be limited in its amount of translational movement relative to the tibia due to its position adjacent to the medial malleolus, tibial plafond, and fibula. Less the AP direction, translational ROM was not significantly different between joints. As these translations were nonzero, our results suggest that each joint undergoes six degree-of-freedom motion rather than rotational motion alone.

The general trends of the dynamic joint angles from our study were comparable to prior dual fluoroscopy studies (Table 1) [19,22,23]. For example, Peltz et al. showed dynamic trends similar to our results for subtalar In/Ev and IR/ER, despite the fact that they imaged subjects while running. A study by Koo et al. presented relatively constant subtalar In/Ev and IR/ER angles, whereas we showed increased eversion and external rotation following heelstrike and decreased eversion and external rotation prior to toe-off. Such differences could be attributed to how Koo et al. defined the shared anatomical coordinate system between the tibia and talus. Also, participants in the study by Koo et al. walked on a short walkway, which might have prevented natural gait and/or the establishment of steady-state gait. Our subjects performed several gait cycles (~30 s to 2 min) before we acquired dual fluoroscopy images, and thus, it is more likely that the participants in our study had achieved steady-state gait.

Balanced heel-rise, an activity that likely requires coordinated stability at the hindfoot has only been investigated in one study that made use of fluoroscopic techniques. Yamaguchi et al. found that the tibiotalar and subtalar joint provided plantarflexion and eversion, respectively, during a heel-rise activity (Table 1) [33]. However, we measured larger angular ROM in the subtalar joint during D/P and IR/ER than that observed by Yamaguchi (Table 1). Also, the translational ROM for the Yamaguchi et al. study was reported to be 2 mm for the tibiotalar joint and nearly zero for the subtalar joint in the AP direction. However, our subtalar translational ROM in the AP direction was greater than that of our tibiotalar joint and larger than zero, in disagreement with the results of the Yamaguchi study. These discrepancies may be due to the fact that Yamaguchi employed single-plane fluoroscopy, which may lack the accuracy necessary to measure translations or rotations that occur out-of-plane of the fluoroscope [33,34]. Also, the heel-rise activity in the Yamaguchi study was achieved by having the subject suspend their heel off a stair, which differs from the balanced heel-rise activity we imaged.

Fig. 4 Mean (bars = 95% confidence intervals) tibiotalar (gray) and subtalar (white) rotational (left) and translational (right) range of motion (ROM) during 0.5 m/s captured gait (top), 1.0 m/s captured gait (middle) and single-leg balanced heel-rise (bottom). Rotational angles reported per dorsi/plantarflexion (D/P), inversion/eversion (In/Ev), and internal/external rotation (IR/ER). Translational distance travel reported in the medial/lateral (ML), anterior/posterior (AP), and superior/inferior (SI) directions; * $p \leq 0.04$.

Table 1 Comparison of range of motion (ROM) values from the current study with ROM values from previous studies using dual fluoroscopy (unless otherwise noted): de Asla et al., Koo et al., Peltz et al., and Yamaguchi et al. Values reported represent mean $\pm$ standard deviation unless otherwise noted. HS = heelstrike, MS = midstance, and TO = toe-off.

		Gait						Heel-rise	
		Current study ^a		de Asla et al. [19] ^b				Current study ^a	Yamaguchi et al. [33] ^{c,d}
		0.5 m/s	1.0 m/s	HS to MS	MS to TO	Koo et al. [25]	Peltz et al. [23]		
Tibiotalar angles (deg)	D/P	14.9 (12.0, 17.8)	16.3 (13.1, 19.5)	9.1 $\pm$ 5.3	4.4 $\pm$ 13.0	18.5 $\pm$ 3.5	28.2 $\pm$ 8.3	33.7 (27.1, 40.3)	39
	In/Ev	4.6 (2.4, 6.9)	3.8 (2.5, 5.1)	-0.1 $\pm$ 2.6	-1.7 $\pm$ 2.7	5.1 $\pm$ 1.1	2.9 $\pm$ 1.2	3.4 (2.2, 4.6)	1
	IR/ER	6.9 (4.8, 9.0)	7.4 (4.4, 10.1)	3.8 $\pm$ 8.2	-1.6 $\pm$ 5.9	8.6 $\pm$ 3.9	7.0 $\pm$ 1.4	8.3 (5.8, 10.8)	11
Subtalar angles (deg)	D/P	7.9 (5.3, 10.4)	8.6 (6.1, 11.1)	-0.9 $\pm$ 1.2	8.5 $\pm$ 2.9	6.6 $\pm$ 2.8	3.6 $\pm$ 1.7	6.7 (4.3, 9.2)	2
	In/Ev	11.6 (8.6, 14.6)	11.3 (9.5, 13.1)	-1.7 $\pm$ 2.7	-10.7 $\pm$ 3.8	6.6 $\pm$ 4.5	7.4 $\pm$ 3.4	9.0 (6.3, 11.6)	11
	IR/ER	10.7 (6.7, 14.7)	12.5 (9.8, 15.2)	-1.5 $\pm$ 9.9	12.3 $\pm$ 8.3	5.6 $\pm$ 2.7	4.5 $\pm$ 1.8	9.01 $\pm$ 1.08	2

^aResults reported as mean (95% confidence interval).

^bReported values were determined from three simulated stance phase positions: heelstrike, midstance, and toe-off.

^cSubjects performed activity at self-selected speed.

^dReported values were estimated from plots provided. Study utilized single-plane fluoroscopy.

Rotational ROM results reported herein demonstrated some similarities and differences when compared to prior research (Table 1). A dual fluoroscopy study by de Asla et al. demonstrated that the tibiotalar joint contributes more D/P than the subtalar joint, while the subtalar joint provides more In/Ev and IR/ER than the tibiotalar joint, which is in agreement with our results [19]. However, our ROM results were larger than those measured by de Asla et al. (Table 1). Discrepancies may be due to the fact that de Asla et al. examined static poses of the gait cycle (i.e., = heelstrike and toe-off), which would not incorporate the natural movement of the hindfoot caused by inertial effects. It has been shown that kinematics differ between weight-bearing and nonweight-bearing activities [33]; similar differences could be observed as a result of inertial effects. Our ROM results were in better agreement with the results obtained by Koo and Peltz, especially for the tibiotalar joint (Table 1). Larger discrepancies were observed at the subtalar joint, where we measured larger angular ROM than Koo and Peltz. These discrepancies may be explained by differences in how coordinate systems were defined. Depending on the orientation of each axis, the coordinate systems could have coupled rotations in more than one anatomical direction. For example, an AP axis offset in the ML direction could incorporate D/P rotation into calculations of In/Ev. Differences in results between studies may also be explained by variations in the activity performed. For example, the portion of gait captured by Peltz did not include toe-off. As evident by our plots (Fig. 2), it appeared that the subtalar joint experienced large changes in In/Ev and IR/ER during toe-off, which may explain why our subtalar ROM results were larger than that reported by Peltz.

Despite the knowledge gained from our study, there were limitations that warrant discussion. First, we were unable to capture the entire stance phase during walking as the foot progressed beyond the combined field of view of the dual fluoroscopy system by motion of the treadmill. This required us to capture the beginning (heelstrike) and end (toe-off) of stance as separate trials, thereby limiting midstance. We acknowledge that treadmill gait is not equivalent to overground walking [35]. However, use of treadmill gait allowed for a more constant step length and cadence, which helped us to time the acquisition of dual fluoroscopy images [36]. Another potential limitation is that we analyzed gait at relatively low speeds, which may limit the generalizability of our results. These walking speeds were selected to provide baseline data to compare to patients, who may have difficulties ambulating faster than 1.0 m/s. Additionally, some trials were missing dual

fluoroscopy images of the entire hindfoot region. We were unable to collect additional trials because we would have exceeded the radiation exposure limits approved for our study. Along these lines, the screening radiographs, dual fluoroscopy, and CT exposed volunteers to radiation. The radiation exposure for each volunteer in the current study did not exceed 0.1 mSv, or approximately 11 days of natural background radiation. Finally, the observed variation in dynamic joint angle magnitude may be a byproduct of assigning coordinate systems to each subject independently. Still, the ROM data, which represent the key findings of our study, were not influenced by variation caused by coordinate system definition.

In conclusion, our results, which demonstrate that the tibiotalar joint provides primarily D/P and the subtalar joint yields In/Ev coupled with IR/ER, largely confirm clinical intuition and prior in vitro and in vivo studies [2-4,6-9, 11-13,29-31,37-40]. However, our data also suggest that the tibiotalar joint provides secondary In/Ev and IR/ER motion, and the subtalar also yields D/P movement. Both joints also provide translational motion, which, when combined with their rotational motion, requires full 6DOF to accurately represent the articulation of the tibiotalar and subtalar joints. The manner in which such secondary contributions articulate the foot/ankle and modulate disease will need to be an area of future investigation. Still, our data of nonpathologic controls serve as foundational data for future studies. In particular, with sub-millimeter and subdegree accuracy, dual fluoroscopy may be a valuable imaging tool to detect what may be small, but clinically significant differences in hindfoot kinematics among patients with ankle pathology. Application of dual fluoroscopy may also provide an objective tool to prognosticate on the ability of surgery to restore normative kinematics, or the possible complications of certain surgical procedures to treat OA, such as tibiotalar fusion.

Acknowledgment

The authors acknowledge the contributions of Madeline Singer, Michael Austin West, Tyler Skinner, and Justine Goebel.

The funding from the National Institutes of Health (Grant No. R21AR063844 and S10RR026565), LS-Peery Discovery Program in Musculoskeletal Restoration, and the American Orthopaedic Foot and Ankle Society (with funding from the Orthopaedic Foot and Ankle Outreach and Education Fund (OEF) and the Orthopaedic Research and Education Foundation (OREF) with designation to the OEF) is gratefully acknowledged. The content is solely the responsibility of the authors

and does not necessarily represent the official views of the National Institutes of Health, the LS-Peery Foundation or the American Foot and Ankle Society.

Nomenclature

AP = anterior–posterior
 CI = confidence interval
 CT = computed tomography
 D/P = dorsi/plantarflexion
 In/Ev = inversion/eversion
 IR/ER = internal/external rotation
 ML = medial–lateral
 OA = osteoarthritis
 ROM = range of motion
 SI = superior–inferior
 3D = three-dimensional

References

- [1] Kuettnner, K. E., and Cole, A. A., 2005, “Cartilage Degeneration in Different Human Joints,” *Osteoarthritis Cartilage*, **13**(2), pp. 93–103.
- [2] Lapidus, P. W., 1963, “Kinesiology and Mechanical Anatomy of the Tarsal Joints,” *Clin. Orthop. Relat. Res.*, **30**(1), pp. 20–36.
- [3] Morris, J. M., 1977, “Biomechanics of the Foot and Ankle,” *Clin. Orthop. Relat. Res.*, **122**, pp. 10–17.
- [4] Oatis, C. A., 1988, “Biomechanics of the Foot and Ankle Under Static Conditions,” *Phys. Therapy*, **68**(12), pp. 1815–1821.
- [5] Levangie, P. K., and Norkin, C. C., 2011, *Joint Structure and Function: A Comprehensive Analysis*, FA Davis, Philadelphia, PA.
- [6] Goto, A., Morimoto, H., Itoharu, T., Watanabe, T., and Sugamoto, K., 2009, “Three-Dimensional in vivo Kinematics of the Subtalar Joint During Dorsi-Plantarflexion and Inversion-Eversion,” *Foot Ankle Int.*, **30**(5), pp. 432–438.
- [7] Wright, D. G., Desai, S. M., and Henderson, W. H., 1964, “Action of the Subtalar and Ankle-Joint Complex During the Stance Phase of Walking,” *J. Bone Joint Surg. Am.*, **46**, pp. 361–382.
- [8] Close, J. R., Inman, V. T., Poor, P. M., and Todd, F. N., 1967, “The Function of the Subtalar Joint,” *Clin. Orthop. Relat. Res.*, **50**(1), pp. 159–179.
- [9] Ting, A. J., Tarr, R. R., Sarmiento, A., Wagner, K., and Resnick, C., 1987, “The Role of Subtalar Motion and Ankle Contact Pressure Changes From Angular Deformities of the Tibia,” *Foot Ankle*, **7**(5), pp. 290–299.
- [10] Hicks, J. H., 1953, “The Mechanics of the Foot. I. The Joints,” *J. Anat.*, **87**(4), pp. 345–357.
- [11] Lundberg, A., Svensson, O. K., Nemeth, G., and Selvik, G., 1989, “The Axis of Rotation of the Ankle Joint,” *J. Bone Joint Surg. Br.*, **71**(1), pp. 94–99.
- [12] Leardini, A., Stagni, R., and O’Connor, J. J., 2001, “Mobility of the Subtalar Joint in the Intact Ankle Complex,” *J. Biomech.*, **34**(6), pp. 805–809.
- [13] Kirby, K. A., 2001, “Subtalar Joint Axis Location and Rotational Equilibrium Theory of Foot Function,” *J. Am. Podiatr. Med. Assoc.*, **91**(9), pp. 465–487.
- [14] Valderrabano, V., Nigg, B. M., von Tscharner, V., Stefanyshyn, D. J., Goepfert, B., and Hintermann, B., 2007, “Gait Analysis in Ankle Osteoarthritis and Total Ankle Replacement,” *Clin. Biomech. (Bristol, Avon)*, **22**(8), pp. 894–904.
- [15] Gorton, G. E., III, Hebert, D. A., and Gannotti, M. E., 2009, “Assessment of the Kinematic Variability Among 12 Motion Analysis Laboratories,” *Gait Posture*, **29**(3), pp. 398–402.
- [16] Bauman, J. M., and Chang, Y. H., 2010, “High-Speed X-Ray Video Demonstrates Significant Skin Movement Errors With Standard Optical Kinematics During Rat Locomotion,” *J. Neurosci. Methods*, **186**(1), pp. 18–24.
- [17] Bonnechere, B., Sholukha, V., Salvia, P., Rooze, M., and Van Sint Jan, S., 2015, “Physiologically Corrected Coupled Motion During Gait Analysis Using a Model-Based Approach,” *Gait Posture*, **41**(1), pp. 319–322.
- [18] de Asla, R. J., Kozánek, M., Wan, L., Rubash, H. E., and Li, G., 2009, “Function of Anterior Talofibular and Calcaneofibular Ligaments During In-Vivo Motion of the Ankle Joint Complex,” *J. Orthop. Surg. Res.*, **4**(1), pp. 4–7.
- [19] de Asla, R. J., Wan, L., Rubash, H. E., and Li, G., 2006, “Six DOF in vivo Kinematics of the Ankle Joint Complex: Application of a Combined Dual-Orthogonal Fluoroscopic and Magnetic Resonance Imaging Technique,” *J. Orthop. Res.*, **24**(5), pp. 1019–1027.
- [20] Caputo, A. M., Lee, J. Y., Spritzer, C. E., Easley, M. E., DeOrio, J. K., Nunley, J. A., and DeFrate, L. E., 2009, “in vivo Kinematics of the Tibiotalar Joint After Lateral Ankle Instability,” *Am. J. Sports Med.*, **37**(11), pp. 2241–2248.
- [21] Campbell, K. J., Wilson, K. J., LaPrade, R. F., and Clanton, T. O., 2014, “Normative Rearfoot Motion During Barefoot and Shod Walking Using Biplane Fluoroscopy,” *Knee Surg. Sports Traumatol. Arthrosc.*, **24**(4), pp. 1402–1408.
- [22] Koo, S., Lee, K. M., and Cha, Y. J., 2015, “Plantar-Flexion of the Ankle Joint Complex in Terminal Stance is Initiated by Subtalar Plantar-Flexion: A Bi-Planar Fluoroscopy Study,” *Gait Posture*, **42**(4), pp. 424–429.
- [23] Peltz, C. D., Haladik, J. A., Hoffman, S. E., McDonald, M., Ramo, N. L., Divine, G., Nurse, M., and Bey, M. J., 2014, “Effects of Footwear on Three-Dimensional Tibiotalar and Subtalar Joint Motion During Running,” *J. Biomech.*, **47**(11), pp. 2647–2653.
- [24] Wang, B., Roach, K. E., Kapron, A. L., Fiorentino, N. M., Saltzman, C. L., Singer, M., and Anderson, A. E., 2015, “Accuracy and Feasibility of High-Speed Dual Fluoroscopy and Model-Based Tracking to Measure in vivo Ankle Arthrokinematics,” *Gait Posture*, **41**(4), pp. 888–893.
- [25] Fiorentino, N. M., Kutschke, M. J., Atkins, P. R., Foreman, K. B., Kapron, A. L., and Anderson, A. E., 2015, “Accuracy of Functional and Predictive Methods to Calculate the Hip Joint Center in Young Non-Pathologic Asymptomatic Adults With Dual Fluoroscopy as a Reference Standard,” *Ann. Biomed. Eng.*, **44**(7), pp. 2168–2180.
- [26] Kadaba, M. P., Ramakrishnan, H. K., and Wootten, M. E., 1990, “Measurement of Lower Extremity Kinematics During Level Walking,” *J. Orthop. Res.*, **8**(3), pp. 383–392.
- [27] Bey, M. J., Zauel, R., Brock, S. K., and Tashman, S., 2006, “Validation of a New Model-Based Tracking Technique for Measuring Three-Dimensional, in vivo Glenohumeral Joint Kinematics,” *ASME J. Biomech. Eng.*, **128**(4), pp. 604–609.
- [28] Winter, D. A., 2005, *Biomechanics and Motor Control of Human Movement*, Wiley, Hoboken, NJ.
- [29] Siegler, S., Chen, J., and Schneck, C. D., 1988, “The Three-Dimensional Kinematics and Flexibility Characteristics of the Human Ankle and Subtalar Joints—Part I: Kinematics,” *ASME J. Biomech. Eng.*, **110**(4), pp. 364–373.
- [30] Engsborg, J. R., 1987, “A Biomechanical Analysis of the Talocalcaneal Joint—In Vitro,” *J. Biomech.*, **20**(4), pp. 429–442.
- [31] McMaster, M., 1976, “Disability of the Hindfoot After Fracture of the Tibial Shaft,” *J. Bone Joint Surg. Br.*, **58**(1), pp. 90–93.
- [32] Stormont, D. M., Morrey, B. F., An, K. N., and Cass, J. R., 1985, “Stability of the Loaded Ankle. Relation Between Articular Restraint and Primary and Secondary Static Restraints,” *Am. J. Sports Med.*, **13**(5), pp. 295–300.
- [33] Yamaguchi, S., Sasho, T., Kato, H., Kuroyanagi, Y., and Banks, S. A., 2009, “Ankle and Subtalar Kinematics During Dorsiflexion-Plantarflexion Activities,” *Foot Ankle Int.*, **30**(04), pp. 361–366.
- [34] Moro-oka, T. A., Hamai, S., Miura, H., Shimoto, T., Higaki, H., Fregly, B. J., Iwamoto, Y., and Banks, S. A., 2007, “Can Magnetic Resonance Imaging-Derived Bone Models be Used for Accurate Motion Measurement With Single-Plane Three-Dimensional Shape Registration?,” *J. Orthop. Res.*, **25**(7), pp. 867–872.
- [35] Schache, A. G., Blanch, P. D., Rath, D. A., Wrigley, T. V., Starr, R., and Bennell, K. L., 2001, “A Comparison of Overground and Treadmill Running for Measuring the Three-Dimensional Kinematics of the Lumbo-Pelvic-Hip Complex,” *Clin. Biomech. (Bristol, Avon)*, **16**(8), pp. 667–680.
- [36] Riley, P. O., Paolini, G., Della Croce, U., Paylo, K. W., and Kerrigan, D. C., 2007, “A Kinematic and Kinetic Comparison of Overground and Treadmill Walking in Healthy Subjects,” *Gait Posture*, **26**(1), pp. 17–24.
- [37] Donatelli, R., 1995, *The Biomechanics of the Foot and Ankle*, FA Davis, Philadelphia.
- [38] Isman, R. E., and Inman, V. T., 1968, “Anthropometric Studies of the Human Foot and Ankle,” Biomechanics Laboratory, University of California, Oakland, CA.
- [39] Stagni, R., Leardini, A., O’Connor, J. J., and Giannini, S., 2003, “Role of Passive Structures in the Mobility and Stability of the Human Subtalar Joint: A Literature Review,” *Foot Ankle Int.*, **24**(5), pp. 402–409.
- [40] Leardini, A., O’Connor, J. J., Catani, F., and Giannini, S., 1999, “Kinematics of the Human Ankle Complex in Passive Flexion: A Single Degree of Freedom System,” *J. Biomech.*, **32**(2), pp. 111–118.