In Vivo Kinematics of the Healthy Ankle Using Weight-Bearing CT

James Clancy, DPM[1], Richard Obert, MS[2], Mark Myerson, MD[3], Mathew Anderle, MPH[4], Daniel Lee, MEng[4], Laura Brinker, DPM[4]

[1]Orthopedic Center of Palm Beach County, [2]Focus Medical Design & Development, [3]Steps2Walk, [4]Paragon 28, Inc.

Statement of Purpose

- The goal of this study was to determine the three-dimensional (3D), weight-bearing kinematics of the healthy ankle during simulated gait using a novel 3D registration technique.

Literature Review

- There is considerable debate in the literature regarding the path of tibiotalar motion.
- Isman and Inman defined the talocrural joint axis as a truncated cone with its apex pointed medially.[1]
- Siegler also found that the talus could be modeled as a truncated cone; however, they determined that its apex is located laterally.[2]
- Others have reported that the axis of rotation changes throughout plantar and dorsi-flexion.[3,4]
- A variety of techniques have been used to determine the in vivo motions of the healthy ankle during gait.[5,6,7]
- These studies conclude that during gait, the dominant rotation of the ankle is in the sagittal plane (dorsi/plantar flexion) with lesser amounts of internal/external and varus/valgus rotation.

Methods

- After IRB approval, 17 subjects with healthy right ankles (9 male, 8 female) underwent weight-bearing CT scans during three phases of a truncated portion of simulated gait (Table 1, Figures 1- 3).
- CT scans were segmented (Materialize Mimics v21, Leuven, Belgium) to isolate tibia, fibula, and talus bones in early stance (ES, after heel-strike), mid-stance (MS), and late stance (LS, before toe-off) and imported into a CAD package for analysis (SolidWorks 2017, Waltham, MA).
- All subjects were previously deemed to have a healthy right ankle by the surgeon investigator (JC) via radiographic evaluation and questionnaire.

Table 1: Subject demographics.

	Height (in.)	Weight (lb)	Age (years)
Average	67.1	162.2	34.9
Standard Deviation	4.1	37.8	10.2

Figure 1: A subject positioned at early stance in the weight-bearing CT scanner. Note that the contralateral limb is trailing the limb of interest.

Methods-Continued

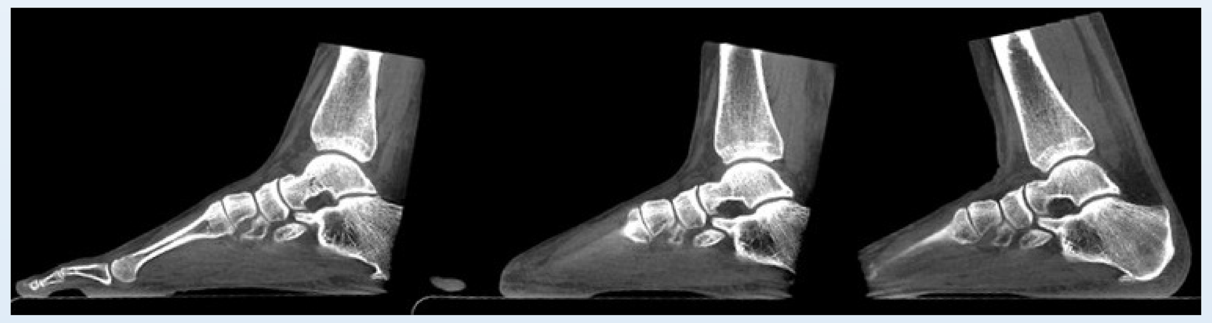

Figure 2: Weight-bearing CT images for a subject at early stance (left), mid-stance (middle) and late stance (right).

Figure 3: Volume render of a subject during late stance.

- Landmarks were established on the mid-stance bones and measurements were obtained for flexion, internal/external rotation, and varus/valgus (inversion/eversion).
- Models of the mid-stance bone were registered to the surface models of the tibia and talus of the other stance positions using a global registration.
- Transformation matrices between the positions of the mid-stance bones registered in early and late stance were determined for each bone and stance combination.
- These transformations were then applied within the CAD system to the mid-stance bones that contained the coordinate system information and the angular measurement process was repeated for each stance, using the landmarks established in the mid-stance scan (Figures 4).

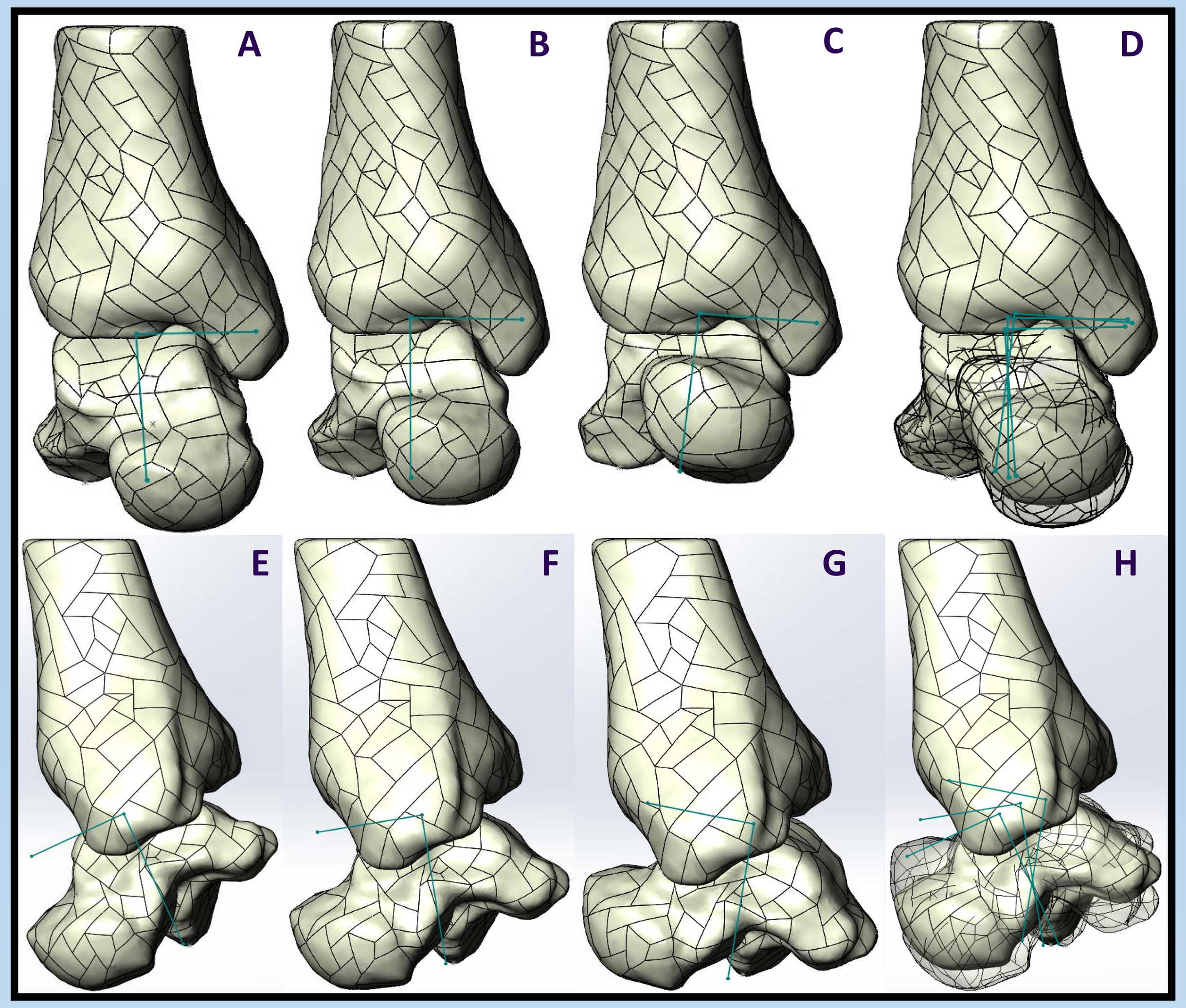

Figure 4: Frontal (top) and sagittal (bottom) views of relative positions of three-dimensional models of the distal tibia and talus for a subject positioned at early stance (A,E), mid-stance (B,F), late stance (C,G) and a comparison of all three stance positions (D,H).

Methods-Continued

- Data analysis was conducted at an $\alpha = 0.05$ level (Sigma Stat 4.0, San Jose, CA & Minitab 16, State College, PA).
- Repeated measures ANOVA was used to analyze differences between phases of gait for each angular parameter.
- Each measurement parameter at each increment was compared against a hypothesized value of zero.
- Parametric methods were primarily used, however non-parametric analysis was performed, where appropriate.

Results

- On average, for ES, MS and LS, respectively, subjects experienced (talus relative to the tibia , Figure 5):
  - -4.6°, 4.1°, and 14.1° of dorsi (+) / plantar (-) flexion
  - -4.3°, -3.7°, and -1.0° of internal (-) / external (+) rotation
  - 1.3°, 1.0°, and 2.0° of varus (-) / valgus (+) rotation
- Each flexion angle was determined to be significantly different from zero, including the mid-stance (Table 2). This is consistent with previous results in the literature, which show mid-stance flexion angles in the range of 5°-10° of dorsiflexion.[8,9]
- The internal/external rotation angle departs significantly from zero in ES and MS.
- Furthermore, the amount of internal/external rotation was significantly less at LS compared to MS (P=.013) and ES (P<.001).
- For varus/valgus, only plantar-flexion had a significant difference from 0°, with a tendency towards valgus.

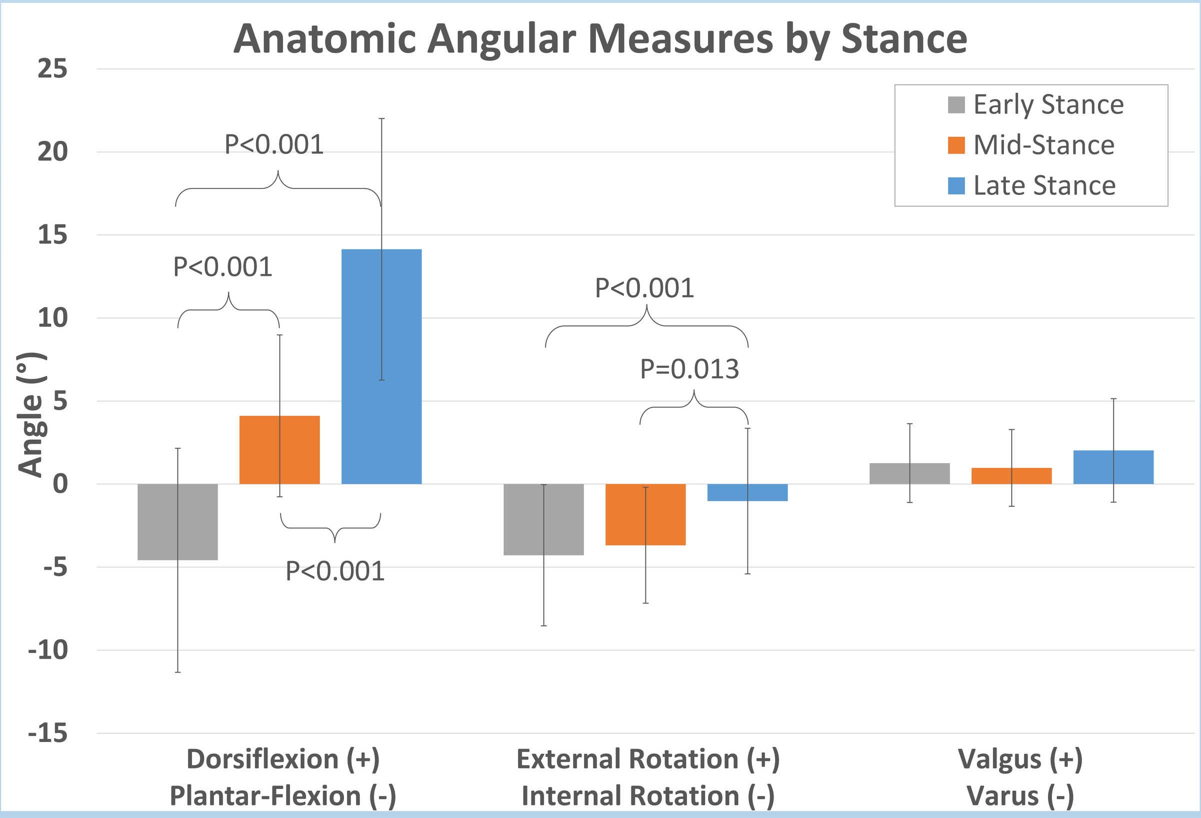

Figure 5: Average anatomic angular measures by stance phase (± standard deviation). Statistically different pairwise comparisons are noted with a bracket and P-value.

Results-Continued

Table 2: Mean and median rotation values with corresponding P-values. Values statistically different from zero are noted with an *.

Measurement Parameter	Mean / (Median)	P-value
Dorsi (+) / Plantar (-) Flexion Angle (°)		
Early Stance	(-6.15)	0.009*
Mid-Stance	-4.11	0.003*
Late Stance	(11.56)	<0.001*
Internal (-) / External (+) Rotation Angle (°)		
Early Stance	-4.28	<0.001*
Mid-Stance	-3.49	<0.001*
Late Stance	-1.02	0.352
Varus (-) / Valgus (+) Angle (°)		
Early Stance	1.27	0.043*
Mid-Stance	0.97	0.102
Late Stance	2.03	0.161

Analysis & Discussion

- Healthy joint motion is driven by the forces acting on the joint and the geometry of the articulating surfaces.
- The results of the current study indicate that the healthy ankle joint experiences varying, tri-axial rotation during gait.
- Therefore, the tibiotalar interface must be conducive to multiple axes of rotation.
- Implants designed to replicate healthy ankle kinematics should allow for varying axes of rotation, which may lengthen implant life.
- Weight-bearing CT technology can be used to help understand joint motion in the foot and ankle.
- The limitations of this study include: restricted or altered motion due to imaging constraints, inconsistencies of foot positioning due to foot size and a small sample size that lacked diversity.

References

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Disclosure

This study was paid for by Paragon 28, Inc. Three authors as indicated above are employed by Paragon 28, Inc.