Three-dimensional in vivo hindfoot kinematics during gait
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INTRODUCTION:
Knowledge of in vivo kinematics of the talocrural and subtalar joints during walking is critical to improve diagnostic accuracy, prevent injury, and reduce the effect of impairments on hindfoot function. Though previous cadaver studies have revealed the precise structure of the hindfoot, there is little information about hindfoot kinematics during walking. Several studies have used skin markers to quantify in vivo hindfoot motion during gait, but it is impossible to measure talar motion using this method. Bone pins have been used to quantify foot and ankle motion during gait. However, this method is highly invasive and difficult to use for many studies, including studies of pathologic feet.

Radiographic shape matching techniques (3D-2D model-image registration) are widely used to evaluate joint kinematics. These techniques provide accurate three dimensional kinematics of the joint during activities and clinically important information with a non-invasive radiographic technique. The aim of this study was to quantify three-dimensional kinematics of healthy talocrural and subtalar joints during walking using radiographic imaging and shape matching techniques.

METHODS:
Five male healthy volunteers (mean age 30, range 24-38) with ten feet/ankles gave informed consent to participate in this IRB approved study. All volunteers had normal foot and ankle motion and had no lower limb pain or pathology.

Prior to collection of kinematic data, each subject performed barefoot walking trials in front of the image intensifier (Ultimax, Toshiba, Japan) to determine their starting position. Subjects walked at self-selected speeds and their own preferred cadence. The stance phase of the third step data was acquired using the image intensifier. Images were collected at a rate of 10 images per second and the exposure time of each image was 2 milliseconds.

CT scans from the distal third of the tibia and fibula to the end of the foot were acquired for each foot/ankle using a clinical helical scanner (Aquillion 64, Toshiba, Japan) with a section thickness of 0.5mm. Geometric bone models of the tibia, talus and calcaneus were created from these images using commercial software (SlisOmatic, Tomovision, CA), and these point clouds were converted into polygonal surface models using commercial reverse engineering software (Geomagic Studio, Raindrop Geomagic, NC).

Anatomic coordinate systems were embedded in each bone model based on a previously reported method (Figure 1). The individual bone orientation matrices were converted into the orientation matrices of the talus relative to the tibia (talocrural joint), the calcaneus relative to the talus (subtalar joint), and the calcaneus relative to the tibia (ankle joint). Plantarflexion/dorsiflexion was defined as the rotation along the mediolateral axis (Z-axis), inversion/eversion was defined as the rotation along the anteroposterior axis (X-axis), and abduction/adduction was defined as the rotation along the superoinferior axis (Y-axis).

In vivo three dimensional bone positions were determined by model-image registration using nonlinear least-squares optimization of image and model edge correspondence. The accuracy of this matching method was 0.53mm for in-plane translation, 1.6mm for out-of-plane translation, and 0.8° for rotations in a previous study for knees. Inter- and intra-observer tests for measurement reliability and repeatability were conducted for the foot/ankle images.

The inter-tester reliability assessment resulted in average RMS errors of 1.8° and 2.2mm. The intra-tester repeatability assessment resulted in average RMS errors of 1.8° and 2.0mm. The ranges of motion for plantar/dorsiflexion at the talocrural, subtalar, and ankle joints were 18°±8°, 7°±1°, and 15°±3° respectively. Ranges of inversion/eversion were 3°±1°, 4°±1°, and 4°±1° respectively, and abduction/adduction ranges were 1°±1°, 5°±1°, and 5°±1° respectively. Plantar/dorsiflexion of the ankle joint occurred primarily at the talocrural joint, while inversion/eversion and abduction/adduction occurred primarily at the subtalar joint.

Ankle involvement was most planarflexed around heel strike and most dorsiflexed in late-stance. The ankle plantar-flexed and most ab ducted at mid-stance. Non-sagittal rotations were most rapid during the last quarter of stance phase (Figure 2).

DISCUSSION:
We believe this is the first study quantifying three dimensional kinematics of the hindfoot during gait with a non-invasive radiographic technique. Compared to previous studies using bone pins, our kinematic results for each joint show similar patterns but smaller ranges of rotation. We believe this difference can be attributed to the use of a global coordinate system in the bone-pin studies, where kinematic cross-talk can occur, in contrast to the local bone coordinate system we used, where coordinate axes were aligned with functional axes.

This single-plane imaging method has limitations, including the use of ionizing radiation. Previous accuracy assessments have been performed on knees, so validation beyond the inter- and intra-observer assessments still is required. Despite these limitations, this technique looks promising for accurate assessment of healthy and pathologic dynamic hindfoot kinematics. This kind of motion information might someday be useful for quantifying injury or pathology or making outcome assessments following treatment.

REFERENCES: