INTRODUCTION
The joints of the rear-foot are subjected to the highest stresses and are the most commonly injured, as compared to the other joints in the human body. Yet, little is known about the in vivo kinematics of the talocrural and subtalar joints. The data available for these joints have typically been presented in terms of the finite helical axis (FHA) and are most often acquired through static cadaver experiments. The FHA representation has been favored over Cardan rotation angles because it lent itself to the measurement tools available, did not have the potential for data singularities and lacked sequence dependency. Thus, the primary purpose of this study was to fully quantify the kinematics of the subtalar, talocrural, and calcaneal-tibial joints in 25 healthy ankles during a volitional task. Using these data, the utility of representing kinematics using the FHA was compared to the Cardan rotation representation. As part of this comparison, the sensitivity of the rotation angles to the selection of the rotation sequence was determined.

METHODS
Twenty healthy subjects participated in this IRB approved study. Time permitting, both ankles were studied. In total data for 25 ankles were collected (age = 26.2 ± 4.5 years; weight = 71.1 ± 13.3 kg; height = 173.6 ± 7.2 cm, 6F/19M).

Subjects were placed supine in a 1.5T MR imager (LX; GE Medical Systems, Milwaukee, WI, USA), after obtaining informed consent. A specialized ankle loading device was used to apply load during plantarflexion (PF), defined as the rotation of the calcaneus about the tibial medial-lateral (M-L) axis. This loading device allowed 3 degrees of rotational freedom at the ball of the foot. Zero degrees of tib-foot PF was defined as when the long axis of the tibia was perpendicular to the plantar surface of the foot. While subjects cyclically plantarflexed and dorsiflexed their ankle at 35 cycles/min, aided by an auditory metronome, fast-PC MR images were collected (anatomic and x, y, z velocity images, temporal resolution =72 ms, imaging time=2:48). The imaging parameters were consistent with prior studies [1]. The sagittal-oblique imaging plane contained the soleus musculotendon junction, tibia, calcaneus, and talus (Figure 1). The 3D time-dependent orientation and displacement of the tibia,

Figure 1: The average FHA overlaid on the left foot images of one subject. Maximum dorsiflexion = dark red, maximum PF = dark green. The FHA is shown to scale and all images are of the same scale (280 mm²). Thus, the length of each FHA represents the amount of rotation occurring at that tib-foot angle. Blue circle = tibial origin. The FHA is shown at 5° increments of tib-foot angle, for clarity.
The talus, and calcaneus were derived through integration of the velocity data [2]. From these data the FHA was determined along with the Cardan rotation angles (zyx-body fixed sequence). Since the FHA is undefined as the angular velocity goes to zero, it was not reported for angular velocities less than 0.25 rad/s. Mean Cardan rotation angles were calculated for the entire population at each tib-foot angle and converted into a series of orientation matrices. Then all 12 non-repeating Cardan rotation angle sequences were calculated for the “mean” matrices. For clarity, only tib-foot PF was reported.

RESULTS
The talocrural and tibiocalcaneal FHAs had similar directions, which were predominantly M-L (Figure 1). The tibiocalcaneal joint displayed the expected supination pattern of plantarflexion with internal rotation and inversion as did the talocrural joint. The PF and inversion directions were fairly consistent throughout the arc of motion, but the axes became less internally directed as the foot plantarflexed. The average direction of the subtalar FHA did not represent the data well, as its direction changed sign in all three planes at least once during ankle plantarflexion for the majority of subjects. The average translation (SD) along the FHA over the arc of motion was -0.5 (1.4), -0.3 (1.4) and -0.6 (1.4) for the talocrural, subtalar and tibiocalcaneal joints, respectively. The total rotation about the FHA (SD) through the arc of motion, averaged across subjects, was 31.7° (11.3°), 15.1° (9.7°) and 29.1° (8.5°) for the talocrural, subtalar and tibiocalcaneal joints, respectively. The high variability reflects the different ranges of tib-foot angle achieved by each subject.

The zyx-Cardan rotation angles agreed with the FHA data, but better represented subtalar kinematics. Across the arc of motion, most ankles demonstrated talocrural and calcaneal-tibial supination, except for five (two with talocrural external rotation, one with external calcaneal-tibial rotation and one with calcaneal-tibial eversion). Subtalar kinematics were the most variable, with three ankles demonstrating pronation. Five, ten and fourteen ankles demonstrated subtalar dorsiflexion, external rotation and eversion, respectively. The tibiocalcaneal and subtalar joints had the largest and smallest translations, respectively.

The selection of Cardan rotation sequence had little effect on the conversion of the direction cosine matrix to rotation angles. The sensitivity to sequence selection ranged from 0.1° to 0.9°, smaller than the inter-subject variability [1].

DISCUSSION
Since the subtalar kinematics are not well defined by the FHA, the Cardan rotation angles are a better descriptor of rear-foot kinematics. Unlike the FHA, Cardan rotation angles are defined when there is zero angular velocity and the initial joint attitude can be incorporated within these angles. The latter may be critical when defining pathologies. Further, the sensitivity to sequence selection was quite small. Thus, rear-foot kinematics are independent of the Cardan rotation sequence. This small sensitivity is likely due to rotation angles that do not exceed a range from -45° to 10°. During an activity with larger rotations in more than one plane (e.g., the hip or shoulder) this finding will likely not hold. Yet, for the ankle joint, the choice of Cardan rotation sequence clearly does not alter the final rotation angles. On the other hand, translations can only be fully understood using knowledge of the FHA location. For example, the large translation of the calcaneus origin can be attributed almost entirely to its origin being at a distance from the calcaneal-tibial FHA.

The use of Cardan rotation angles also clarified the relationship between the motion at the tibiocalcaneal and talocrural joints. Due to the variability of subtalar motion across subjects, the relationship between motion at the tibiocalcaneal and talocrural joints was inconsistent. Thus, assuming any knowledge of subtalar or talocrural motion, based on tibiocalcaneal motion, is not feasible.

REFERENCES