Validation of Foot Bones Segmented from Computed Tomography: Promising Results from a Low Dose Cone Beam Scanner

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INTRODUCTION: Accurate segmentation of foot and ankle bones from computed tomography (CT) scans is an essential precursor to both statistical shape studies and model-based biplanar fluoroscopic tracking. Errors in modeling the bones may propagate into coordinate system definitions or affect arthrokinematic calculations. Cone beam computed tomography scanners with sensitive detectors offer a lower dose alternative to fan beam scanners, although with tradeoffs in signal to noise ratio and tissue contrast [1]. The primary aims of this study were to validate the accuracy of foot bone models generated using established semi-automatic segmentation techniques relative to ground truth laser scans of dissected and denuded bone specimens [2], and to compare the errors in models segmented from a fan beam scanner to those from a low dose CB cone beam scanner.

METHODS: Three fresh-frozen cadaveric feet (48 ± 12.8 years old, 2 males, 1 female, 28.5 ± 7.0 BMI) were obtained and custom fiducial marker clusters were rigidly embedded into the tibia, talus, calcaneus, navicular, first metatarsal, and proximal phalanx of each specimen (Figure 1A). CT scans were acquired (Figure 1B) on a fan beam Siemens Biograph 16 (voxel size: 0.67 x 0.67 x 0.75 mm) and a cone beam CurveBeam LineUp (voxel size: 0.3 x 0.3 x 0.3 mm). Following CT, the bones of interest were excised and denuded of soft tissues. A laser scanning coordinate measurement machine arm (Kreon ACE-7-20 with Solano Blue scanner, calibrated accuracy: 0.005 ± 0.016 mm) was used to scan the bone surfaces and fiducial clusters (Figure 1C). Laser scans were rendered as surface meshes in Geomagic Wrap 2022 software and co-registered to the CT volumes in a least-squares sense using the fiducial cluster data. Registered laser data were voxelized into masks to compare to the segmentations, which were performed in Mimics software (v22, Materialise, Belgium) by three independent operators across three repeated sessions (Figure 1D). The accuracy of the segmentations was compared against the ground truth laser scan data, and repeatability and agreement between and within operators were assessed with intraclass correlation coefficients (ICC). Metrics for assessing segmentation accuracy included bone surface-based error and voxel-based measures like the Dice coefficient and the recall and precision [3].

RESULTS: Across all bones and scans, the average root-mean-square sphere registration error was 0.11 ± 0.17 mm. Excellent ICC scores were observed for all bones, both within operators and between operators (all ICC > 0.990). Cone beam scanner surface-based errors ranged from 0.41± 0.11 mm for the proximal phalanx up to 0.46 ± 0.10 mm in tibias across all bones (Figure 2). Fan beam scanner surface-based errors ranged from 0.64 ± 0.21 for the proximal phalanx up to 0.91 ± 0.15 mm for the tibia. The subtalar regions of the talus and calcaneus in the fan beam scans exhibited the largest overall errors. Across all bones, the average Dice scores were 0.947 ± 0.043 for fan beam and 0.949 ± 0.049 for cone beam scanners. Recall scores were 0.971 ± 0.019 for the fan beam segmentations and 0.963 ± 0.044 for cone beam. Precision scores were 0.909 ± 0.047 for the fan beam segmentations and 0.937 ± 0.035 for cone beam.

DISCUSSION: There were minimal differences in the voxel-based metric scores between scanner types. However, there was a roughly 0.5 mm greater surface-based error on average in the fan beam scans compared to the cone beam scans. This may be attributable to the voxel sizes of the cone beam scanner which has better than twice the resolution of the fan beam scanner used in this study. Thus, despite the noisier images and poorer bone contrast inherent in low dose cone beam CT, operators can reliably and accurately semi-automatically segment foot bones.

SIGNIFICANCE/CLINICAL RELEVANCE: This study offers further evidence in support of the increasing adoption of low dose weightbearing CT for lower extremity imaging. These data establish lower limits on the precision of bone modeling and provide confidence in using semi-automatic segmentation methods on low dose cone beam CT images.

REFERENCES: [1] Lobo et al., Skeletal Radiology, 2022. [2] DeVries et al., Skeletal Radiology, 2008. [3] Taha, et al., BMC Medical Imaging, 2015.

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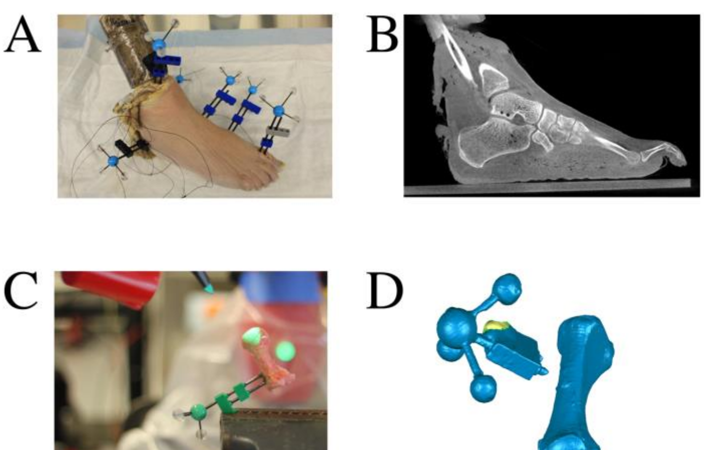

Figure 1: Marker clusters embedded in specimen bones (A), CT scans performed on cone beam and fan beam scanners (B), dissection and laser scanning of bones (C), and ground truth surface mesh generation from laser data.

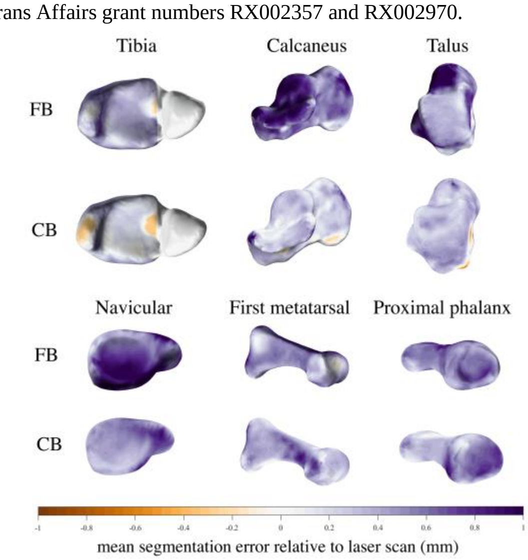

Figure 2: The average segmentation errors for each bone from fan beam (FB) and cone beam (CB) computed tomography scans.