INTRODUCTION:
Three-dimensional (3-D) skeletal motion capture technology, such as X-ray Reconstruction of Moving Morphology (XROMM; Brown University, Providence, RI), currently employs a combination of biplanar video fluoroscopy and computed tomography (CT) to track 3-D skeletal movement in vivo with high accuracy [1-3]. Employing this technology to obtain quantitative data on joint motion requires an understanding of the system’s precision and accuracy. The purpose of this study was to determine 1) the accuracy and 2) the precision of the XROMM system by tracking radio-opaque beads embedded in a bone model and a cadaveric specimen.

METHODS:
XROMM Facility: The biplanar XROMM facility consists of two Varian model G-1086 x-ray tubes, two EMD Technologies model EPS 45-80 pulsed x-ray generators, two 16” Dunlee model TH9447QXH590 image intensifiers (IIs), and two Phantom v9.1 high-speed digital video cameras. The overall resolution of the imaging chain is approximately 2 line pairs/mm. The x-ray tubes are suspended from the ceiling by tube cranes and the IIs are mounted on mobile gantries.

Evaluating Accuracy: A femur bone phantom was embedded with six 1 mm tantalum beads and rigidly fixed to a linear (RT-3 Series, Newmark Systems) and rotary (NB4 Series) stage with accuracies of 0.001 mm and 0.002º, respectively. A reference marker assembly with six 1 mm tantalum beads was rigidly fixed to the base of the stage. The x-ray beams were set up to intersect one another at a beam angle of 91.5º and a source to image distance of 158 cm. The phantom was positioned within the intersecting volume of the two beams. X-ray parameters were 100 kVp and 100 mA. Three trials of 8 linear motions (0, 0.001, 0.01, 0.1, 1, 10, 25, and 50 mm) and three trials of 8 rotational motions (0, 0.002, 0.01, 0.1, 1, 10, 25, and 50º) of the bone phantom were captured and recorded. 3-D marker positions were digitized from the biplanar fluoroscopic images using custom MATLAB software (XrayProject; XROMM, Brown University, Providence, RI). For all linear and rotational trials, rigid body motions of the phantom were calculated with respect to the reference marker assembly [4]. To determine the influence of the number of markers on accuracy these motions were recalculated with various markers sets: all 6 markers, all 5 marker combinations, all 4 marker combinations, and all 3 marker combinations. Linear accuracy was determined as the absolute difference between the rigid body motion and the true linear stage motion. Rotational accuracy was determined as the absolute difference between the rigid body motion and the true rotary stage motion.

Evaluating Precision: Five 1 mm tantalum beads were implanted into the radius, ulna, 1st metacarpal, and 3rd metacarpal of a human cadaver forearm (Figure 1).

Figure 1: X-ray image of the cadaver forearm with 5 tantalum beads (circled in red) implanted into the radius, ulna, 1st metacarpal, and 3rd metacarpal.

The x-ray beams were set up to intersect each other with a beam angle of 86.2º and a source to image distance of 137 cm. X-ray parameters were 85 kVp and 160 mA. 557 frames were captured for a dynamic wrist motion from extension to flexion at 60 frames-per-second. The cameras were shuttered at 500 μs. 3-D marker positions were digitized from the biplanar fluoroscopic images from each frame using custom software (XrayProject). Each bone marker assembly was treated as a separate rigid body, and inter-marker distances were determined for all marker combinations within each rigid body. Precision was determined as the standard deviation of the inter-marker distances.

RESULTS:
Accuracy: The overall mean linear accuracy using marker clusters of 6, 5, and 3 beads were 0.08 ± 0.08 mm, 0.11 ± 0.11 mm, 0.16 ± 0.18 mm, and 0.29 ± 0.37 mm, respectively (Figure 2). The overall mean rotational accuracy using these same clusters were 0.05 ± 0.03º, 0.06 ± 0.05º, 0.08 ± 0.07º, and 0.13 ± 0.12º respectively. Precision: Precision values ranged from 0.07 mm to 0.13 mm (Table 1). As expected, the largest bones tended to have the highest precision and the smaller bones the least precision.

DISCUSSION:
We evaluated the accuracy and precision of a biplanar video fluoroscopy system and found the overall accuracy for the system lies between 0.05 - 0.1 mm and 0.05 – 0.1º, under the given tested conditions. As expected, clusters containing more markers produced better accuracy results; however, the increase in accuracy between 5 and 6 beads wasn’t substantial. The cadaver precision measurements varied from ~ 0.05 mm to ~ 0.1 mm. The poorer precision for the 1st and 3rd metacarpal are thought to result from changing tissue densities from position to position. These results are consistent with those of other 3-D skeletal motion capture technologies [1, 3]. The XROMM system that combines biplanar fluoroscopic and CT data for measuring dynamic 3-D in vivo skeletal motion will permit novel studies on human joint function and studies of accuracy and precision are critical first steps.

REFERENCES:

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