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Accuracy assessment of 3D bone reconstructions using CT: an intro comparison

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ABSTRACT

Computed tomography provides high contrast imaging of the joint anatomy and is used routinely to reconstruct 3D models of the osseous and cartilage geometry (CT arthrography) for use in the design of orthopedic implants, for computer assisted surgeries and computational dynamic and structural analysis. The objective of this study was to assess the accuracy of bone and cartilage surface model reconstructions by comparing reconstructed geometries with bone digitizations obtained using an optical tracking system. Bone surface digitizations obtained in this study determined the ground truth measure for the underlying geometry. We evaluated the use of a commercially available reconstruction technique using clinical CT scanning protocols using the elbow joint as an example of a surface with complex geometry. To assess the accuracies of the reconstructed models (8 fresh frozen cadaveric specimens) against the ground truth bony digitization—as defined by this study—proximity mapping was used to calculate residual error. The overall mean error was less than 0.4 mm in the cortical region and 0.3 mm in the subchondral region of the bone. Similarly creating 3D cartilage surface models from CT scans using air contrast had a mean error of less than 0.3 mm. Results from this study indicate that clinical CT scanning protocols and commonly used and commercially available reconstruction algorithms can create models which accurately represent the true geometry.

1. Introduction

The high contrast provided by X-ray computed tomography (CT) facilitates segmentation of osseous structures from surrounding soft tissue, and this can be used to create three-dimensional (3D) reconstructions. These can be employed in computer assisted surgery, for visualization of bony defects and injuries, and computational dynamic and structural analysis. The accuracy of the 3D bone models used in these applications is paramount to the validity of the information obtained in these studies/procedures. Additionally, with the recent emphasis on patient individualized care, the use of reconstructed bone models to pre-operatively plan and create reverse-engineered orthopedic implants are increasing [1,2]. The accuracy of these 3D reconstructions is essential as an incorrectly shaped implant will not fit the patient [3].

Cartilage 3D reconstructions can also be created using CT with appropriate contrast agents or air [4–7]. Creating 3D reconstructions of cartilage is useful for quantifying morphology, as well as for developing computer models to predict cartilage contact, deformation, and stress.

Accuracies of 3D reconstructions rely on a ground truth measurement for comparison. One method used to assess the accuracy of the reconstruction measures distances between marked anatomical references on the reconstruction and on the physical bone [1,8,9]. These techniques, introduce error when identifying anatomical landmarks as corresponding points [5,8,9]. Additionally, when taking manual measurements, the use of calipers can introduce error [10]. Alternatively, fully 3D measurement approaches have been described in the literature by comparing the surface point cloud "ground truth" data sets obtained using a laser scanner [2,3,11,12] or a contact-type coordinate measuring machine [10]. The errors reported in these studies are for the whole bone examined and are not separated by type/region of bone.

Studies examining 3D reconstructions often rely on machined bone segments or dried bone cadavers and bone analogues. Machined bone segments can be used to reduce the complexity of the accuracy

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measurements obtained [10] but does not reflect the complex geometry of joints and can also introduce error during the machining process [1,5,6]. The use of bone analogues (sawbones) [10,13] or dried cadaveric specimens [1,3,9,12] is also employed but does not necessarily reflect the typical scenario where an intact cadaveric specimen for an *in vitro* application or a patient in an *in vivo* application is scanned and a 3D model is reconstructed.

The accuracy of a 3D reconstruction can depend on the reconstruction technique (algorithm, segmentation parameters, *etc.*) employed, surface geometry, and imaging protocol. The objective of this study was to assess the accuracy of bone and cartilage surface reconstructions through comparison with directly measured bone and cartilage surface topographies, using the elbow as an example of an articulation with a complex surface geometry and for which the accuracy has not been clarified in the literature [10].

2. Materials and methods

2.1. Volumetric image acquisition: X-ray computed tomography

Eight intact cadaveric elbow joints (average age 79 years, range 64–90 years, 6 male, 2 females, 4 left and 4 right) were employed. A computed tomography (CT) scan of elbow joints was obtained prior to testing (Intact CT) (Fig. 1A) using a GE Discovery CT750 HD CT scanner (GE, Waukesha, WI) (292 mA/rotation and 120 kVp). The resulting voxel dimensions were approximately 0.3 × 0.3 × 0.625 mm.

2.2. Specimen preparation

Following imaging, each specimen was disarticulated by separating the proximal radius, ulna and distal humerus. Soft tissues were dissected from each bone while preserving the cartilage surface. Specimens were soaked in saline during preparation to maintain cartilage hydration. Optically-tracked infra-red position sensors were rigidly attached to the humerus, radius and ulna approximately 2–3 in from the articular region of each bone (Fig. 1B).

2.3. Digitization protocol

A pre-calibrated optically tracked stylus was used to digitize the cortical (Fig. 1C) and cartilage surface (Fig. 1D) of each bone (Optotrak Certus®, NDI, Waterloo, ON, Canada). To maintain the in-plane accuracy of 0.1 mm and 0.15 mm perpendicular to the camera, a direct line of sight between the camera and the position sensors was maintained and kept within 2.5 m. The Optotrak motion capture system is an infra-red tracking system. The trackers actively emit infra-red light that is then accurately detected by the camera. The calibrated stylus used was approximately 3 in in length with a pointed tip that was calibrated using a pivot test to calibrate the location of the point with respect to the 'active' optical tracker attached to the stylus (calibrated to 0.1 mm accuracy using a pivot test). Digitizations of the surfaces of the bones and cartilage created 3D point clouds. The accuracy of the stylus has also been compared to a gold standard laser scanner using known-dimensional spheres of varying size (10–28 mm diameter) and had an overall error less than 0.15 mm ± 0.2 mm.

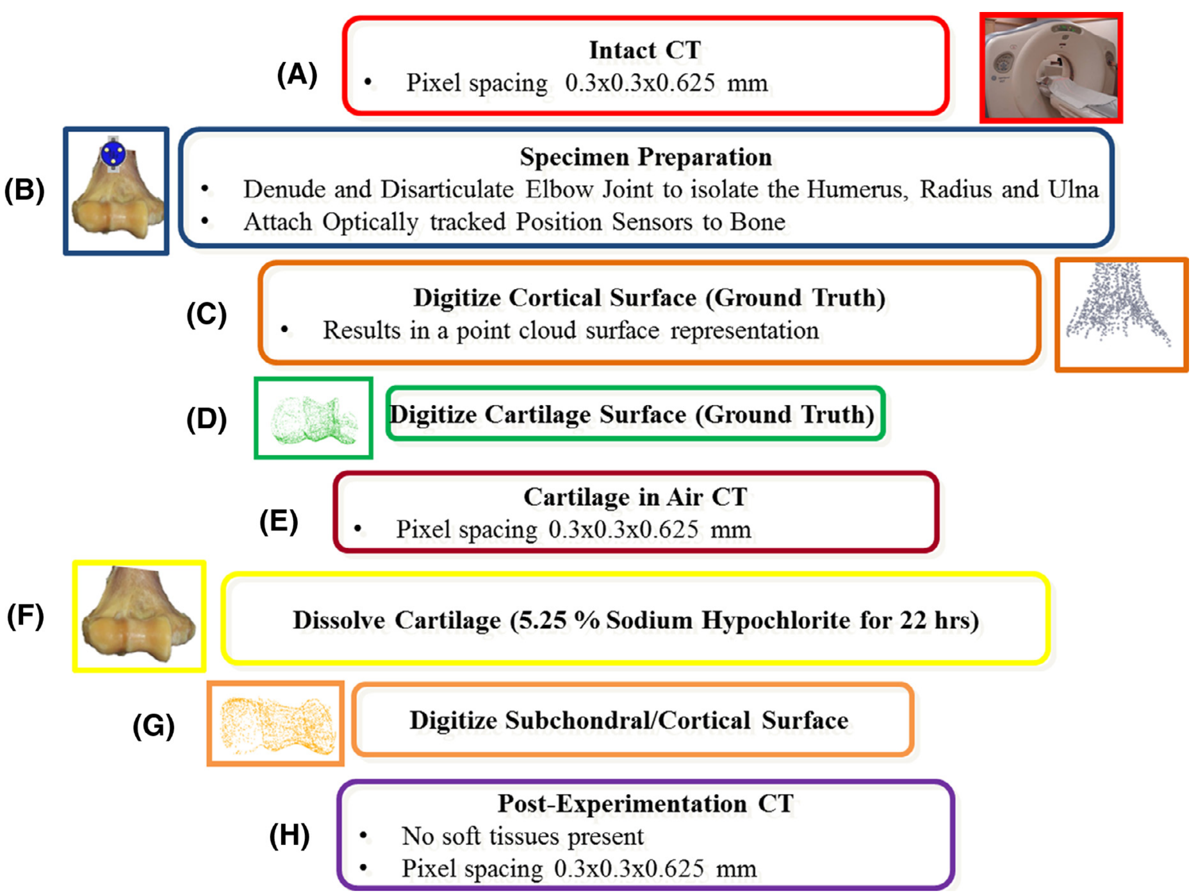

Fig. 1. (A–H) Experimental protocol. (A) Intact CT is acquired for each specimen, (B) Each specimen was then denuded and disarticulated and optical trackers were attached, (C) The cortical surface of the actual bone was digitized (ground truth), (D) The cartilage/articular surface of the actual bone was digitized (ground truth), (E) CT images were acquired of the specimen using 'air' as a contrast agent to visualize the cartilage, (F) Cartilage surface was then dissolved using sodium hypochlorite, (G) The cortical and subchondral regions of the actual bone was then digitized (ground truth), (H) CT images of the specimen was then acquired after the cartilage had been dissolved.