CARPAL CARTILAGE THICKNESS MAPPING USING μCT

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INTRODUCTION

CT image-based computer modeling is increasingly being used to investigate the normal bony articulations in the wrist, as well as the consequences of conformational changes that develop after wrist injury (e.g. scapholunate advanced collapse, or SLAC wrist). The inclusion of cartilage on the CT-generated bone surfaces is necessary to maximize the clinical and biomechanical relevance of these techniques.

This study was performed to evaluate the application of 3-D μCT-generated cartilage thickness maps to carpal bone models generated using a clinical CT scanner. In particular, we evaluated μCT/CT bone congruence, the scalability of cartilage thickness with bone volume, and cartilage penetration at different wrist positions.

METHODS

Clinical CT Scanning and Kinematics Four fresh-frozen cadaver forearms (2M, 2F, ages 66, 69, and 62, 62 respectively) were CT scanned at various positions of flexion, extension, radial and ulnar deviation (pure and combined), and the kinematics of the capitate, lunate, and scaphoid were determined via markerless bone registration (Crisco 1998). The scans were performed at 120 kVp and 80 mA, yielding 3-D volume images with a *z*-axis resolution of 1 mm and an in-plane resolution of 0.3 mm x 0.3 mm (neutral) or 0.9 x 0.9 mm (other positions).
μCT Imaging Following clinical CT imaging, the capitate, lunate, scaphoid and radius were removed via careful dissection. High-resolution (60 μm isotropic voxel size) 3-D images of each bone were generated using a Scanco μCT 40 (Scanco Medical AG, Bassersdorf, Switzerland). The bones were scanned in air (to facilitate cartilage segmentation) using the following settings: 55 kVp, 145μA, 250 ms integration time.
Generation of Bone/Soft Tissue Volumes 3-D bone and soft tissue volumes (cartilage + ligament) were generated via simple thresholding and manual editing (Mimics, Materialise, Ann Arbor, MI).
Alignment of μCT Volumes Each μCT-generated bone was aligned with the corresponding clinical CT-generated bone using Geomagic Studio (Geomagic, Durham, NC). The resulting transforms were then applied to the soft tissue volumes to align them in the same coordinate system.
Assessing μCT and CT Bone Congruence Congruence of the μCT and CT-generated bone models was assessed by comparing the distance between the surfaces of the registered bones, their centroid locations, inertial axes, and calculated bone volumes.
Carpal Cartilage Thickness Quantification The individual cartilage facets on each bone (i.e. the lunate facet on the scaphoid), were manually defined on the soft tissue volumes using Geomagic Studio and then saved as separate surfaces. The shortest distance from the μCT bone surfaces to each of the cartilage facet surfaces was quantified using Geomagic Qualify. Scaling was assessed by regressing the average cartilage thickness for each bone against μCT bone volume.
Assessing Cartilage Penetration The aligned μCT bones and cartilage facets were visualized in nine positions of flexion, extension, radial and ulnar deviation using

the CT-derived kinematic transforms. Penetration was reported on a scale of 0 (no cartilage contact) to 3 (bone penetration).

RESULTS

µCT to CT Congruence The fidelity of the µCT and CT-generated bones was high. On average, the CT-generated bone surface fell outside the µCT-generated bone surface by 0.178 mm, though the regions where one model was larger than the other were randomly distributed (Fig. 1). The centroids were almost identical (Δ = 0.283 mm), while the direction of the inertial axes differed at most by 4.5°. The CT-generated bones were on average 196.0 mm^3 larger than the µCT-generated bones.

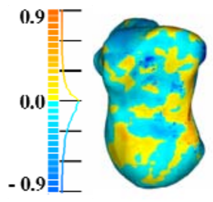

Figure 1 Distance Map, µCT to CT

Scaling of Carpal Cartilage Thickness The average *per bone* carpal cartilage thickness ranged from 0.48 - 1.16 mm and was independent of bone volume (Fig. 2).

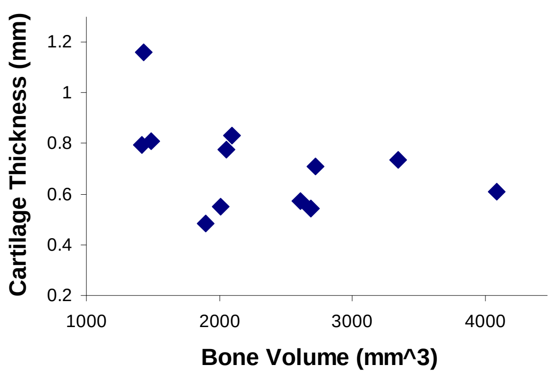

Figure 2 Average cartilage thickness plotted as a function of bone volume (each point is one scaphoid, lunate or capitate)

Cartilage Penetration Cartilage penetration was smallest in the neutral wrist position for all articulating surfaces. Otherwise, penetration was least at the scapho-lunate articulation (Table 1).

Table 1: Average measure (n= 4) of cartilage penetration in various positions

	Cap-Lun	Cap-Sca	Lun-Sca	Lun-Rad	Sca-Rad
Neutral	0.3	1.0	0.1	1.5	1.4
40° F	0.6	1.1	0.5	1.8	1.4
40° E	1.6	1.9	0.1	1.8	2.6
10° R	1.0	0.6	0.3	1.6	1.4
30° U	1.5	0.9	0.1	1.3	1.3
40° F + 30° U	0.9	1.0	0.0	1.5	1.1
40° E + 30° U	2.0	1.9	0.0	1.8	1.9
40°E + 10° R	1.8	1.8	0.3	2.0	2.8
40°F + 10° R	0.6	0.6	0.5	1.4	1.5

DISCUSSION

This study was performed to evaluate the application of µCT-generated cartilage surfaces to clinical CT-generated carpal bone models. Our technique yielded µCT-generated cartilage surfaces that fit the CT-generated bone surfaces with good fidelity, as assessed by µCT and CT-generated bone surface congruence. We were surprised that carpal cartilage did not scale with bone volume, given that the dimensions of the carpal bones increase isometrically with increasing bone volume (Crisco, 2005). We were also surprised by the amount and extent of cartilage-cartilage and cartilage-bone penetration generated using this technique, though they are not unreasonable given the error inherent in aligning the µCT and CT bone models, and the errors associated with calculating kinematics using markerless bone registration, which are on the order of 0.5 mm and 0.5° (Neu 2000).

REFERENCES

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