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μCT-GENERATED CARPAL CARTILAGE SURFACES: VALIDATION OF A TECHNIQUE

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Abstract

Computational models are increasingly being used for the analysis of kinematics and contact stresses in the wrist. To this point, however, the morphology of the carpal cartilage has been modeled simply, either with non-dimensional spring elements (in rigid body spring models) or via simple bone surface extrusions (e.g. for finite element models). In this work we describe an efficient method of generating high-resolution cartilage surfaces via micro-computed tomography (μCT) and registration to CT - generated bone surface models. The error associated with μCT imaging (at 10 μm) was 0.009 mm (95% confidence interval 0.007 – 0.012 mm), or ~1.6% of the cartilage thickness. Registration error averaged 0.33 ± 0.16 mm (97.5% confidence limit of ~0.55 mm in any one direction) and 2.42 ± 1.56 degrees (97.5% confidence limit of ~5.5 degrees in any one direction). The technique is immediately applicable to subject-specific models driven using kinematic data obtained through in vitro testing. However, the ultimate goal would be to generate a family of cartilage surfaces that could be scaled and/or morphed for application to models from live subjects and in vivo kinematic data.

1. Introduction

Abnormal kinematics and altered cartilage contact are believed to precipitate post-traumatic intercarpal osteoarthritis (Peterson and Szabo, 2006). However, direct measurement of intercarpal contact is hampered by the sheer number, small size and variable, position-dependent congruency of the individual articulations (Mayfield, 1984), as well as the complex ligamentous network that must be breached for transducer placement (Berger, 1997). Accordingly, computational approaches are increasingly used for stress analysis in the carpus (Schuind et al., 1995; Iwasaki et al., 1998; Genda and Horii, 2000; Carrigan et al., 2003; Anderson et al., 2005; Guo et al., 2009).

Regardless of the analytical approach, carpal cartilage morphology has typically been modeled simply, for example as a series of non-dimensional compressive springs (Schuind et al., 1995; Iwasaki et al., 1998; Genda and Horii, 2000), or by extruding the segmented

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bone surfaces (Carrigan et al., 2003; Marai et al., 2006; Majima et al., 2008; Guo et al., 2009). In most cases the thickness of the cartilage facets is defined via distance thresholding (Genda and Horii, 2000; Marai et al., 2006; Majima et al., 2008) or FEA element contact (Carrigan et al., 2003; Anderson et al., 2005; Guo et al., 2009). Only recently, with the advent of cryomicrotome-derived anatomic models (Anderson et al., 2005; Dvinskikh et al., 2009), has carpal cartilage modeling advanced to the sub-millimeter level.

In this study we examine micro-computed tomography (μ CT) as a means to generate high-resolution carpal cartilage surfaces from cadaver specimens. The method yields three-dimensional (3-D) cartilage volumes that can be analyzed directly (i.e. for morphologic assessment) or readily registered to CT-generated bone surface models (Figure 1), which can then be coupled with in vitro kinematic data (e.g. Kaufmann et al., 2006; Blankenhorn et al., 2007; Calfee et al., 2008; Fischli et al., 2009; Stilling et al., 2010) and used for FEA or other means of mathematically modeling cartilage contact. The specific objectives of this work, therefore, were to describe the methodology and provide estimates of the two principal sources of error: error associated with segmentation of the cartilage volumes, and error associated with registration of the μ CT-generated cartilage facets to the CT-generated bone models.

2. Methods

2.1 Methodology Overview

Disarticulated carpal bones are μ CT scanned, yielding images in which the bone and soft tissues are easily identified. Soft tissue “shells,” which include both cartilage and ligament remnants, are segmented from the μ CT volume images, and the individual cartilage facets are identified and extracted as separate objects. The cartilage facets are fit to their respective CT-generated bone models using transforms generated by registering the inner (bone) surface of the soft tissue shells to CT-generated bone models. (Detailed methods are included in the cartilage segmentation (2.3) and registration (2.4) sections, below.)

2.2 Validation of μ CT-Generated Cartilage Segmentation

μ CT-generated cartilage segmentation was validated via direct comparison of 2-D μ CT cross-sections with 2-D plane images obtained using a high-resolution flatbed scanner (Figure 2). The scaphoid (sca), lunate (lun), trapezoid (tpd), and two triquetrums (tqm1 and tqm2) were dissected from two unembalmed cadaver wrists (both female, ages 58 and 69), and a single thin (~ 0.27 mm) section was cut from each bone using a low speed saw. Full color 4,800 dpi (~ 5.3 μ m/pixel) TIFF images were generated of each bone slice using a high-resolution flatbed scanner (UMAX 2100XL, Dallas, TX), and the bone-soft tissue and soft tissue-air interfaces were digitized using Analyze 6.0 image analysis software (Biomedical Imaging Resource, Mayo Clinic, Rochester, MN). Corresponding cross-sectional slice images were generated from the same thin sections using a desktop micro-computed tomography system (μ CT 40, Scanco Medical AG, Brütisellen, CH). μ CT scanning was performed at 55kVp and 145 μ A, with an isometric voxel resolution of 10 μ m (2,538dpi). The μ CT images were thresholded to separate the soft tissue (cartilage and ligament) from the bone and background, and representative slice images were exported as TIFF files. The threshold values were selected manually to optimize fidelity with the grayscale images; all of the threshold values were within 3.2% of the mean, which was 620 (Table 1).

The thresholded μ CT slice images were imported into Analyze 6.0 and an edge detection algorithm was used to extract series of discrete points for the inner and outer soft tissue surfaces. The flatbed and μ CT-generated point sets for a given bone were imported into

geomagic® STUDIO® (*geomagic*®, Research Triangle Park, NC) and co-registered. Regions of the contours clearly identified as articular cartilage were selected for thickness quantification and the radial distances from the geometric center to the inner (ID) and outer cartilage (OD) surfaces were calculated for both images at one degree intervals using custom-written *Matlab*® code (Mathworks®, Natick, MA). Cartilage thickness was defined as the distance between the inner and the outer surfaces (OD-ID). A mixed linear model was used to compare the μ CT- and flatbed-calculated cartilage thicknesses (SAS, Cary, NC). 95% confidence intervals were calculated for the difference estimates.

2.3 Validation of Methodology for Registration to Clinical CT-Generated Bone Models

Bone surface registration was validated by comparing the centroid locations and inertial axes of μ CT-generated bone models after registration to clinical CT-generated bone models. Registration of the μ CT-generated bone surfaces yields the transforms that are used to register the individual cartilage facets to the CT-generated bone surfaces for subsequent analysis.

High-resolution 3-D volume images were generated from the scaphoid, lunate and capitate bones from seven cadaver wrists (4 male, 3 female, average age 68.4 ± 6.2 years) using a desktop μ CT system (60 μ m isometric voxel resolution, acquired at 55kVp and 145 μ A). *Mimics*® software (Materialise, Leuven, Belgium) was used to segment and export the μ CT-generated bone surfaces. The bone surfaces were then imported into *geomagic*® STUDIO®, where they were decimated 75%, wrapped and smoothed.

The μ CT-generated bone surfaces were fit to surface models of the same scaphoid, lunate and capitate bones generated using a clinical CT scanner (Calfee et al., 2008). The resolution of the clinical CT scans was 0.3mm $\times$ 0.3mm in-plane, and 1.0mm along the z-axis (slice thickness). Registration of the μ CT-generated bone surfaces to the clinical CT-generated bone surfaces was performed using *geomagic*® STUDIO®. “Fit” of the cartilage surfaces to the CT-generated bones was quantified by comparing the distance between the μ CT-generated bone surfaces (which are the inner surfaces of the soft tissue shells) and the CT generated bone surfaces, as well as their volumes, centroid locations and inertial axes. Mapping of the distances between the two surfaces was performed using *geomagic*® QUALIFY® (*geomagic*®, Research Triangle Park, NC), while the volumes, centroid locations and inertial axes were calculated using custom-written *MatLab*® code. As with the thickness data, the fit data was analyzed using mixed linear models. Follow-up comparisons were performed using the Holm test, which automatically adjusts for alpha inflation.

3. Results

3.1 μ CT-Generated Cartilage Thickness Validation

The contours obtained from the μ CT images aligned well with the contours obtained from the flatbed images (Figure 2), and when the thickness values were compared the differences were small, even when they were statistically significant (Table 1). For two of the five bones (tpd and tqm1) the μ CT and flatbed image-calculated cartilage thickness values were indistinguishable; in another two (sca and lun), the difference in thickness averaged less than 0.001mm (1.0 μ m); and in one (tqm2), the difference in thickness averaged 0.031mm (31.0 μ m). In the three bones where there was a statistically significant difference in μ CT and flatbed image-calculated cartilage thickness, the μ CT image-calculated thickness was slightly larger than the flatbed image-calculated difference.

When all of the thickness measurements were analyzed together (n=5 bones, 698 measurements), the average flatbed image-calculated thickness was 0.753mm and the difference between the μ CT and flatbed image-calculated cartilage thicknesses was

0.009mm. With a 95% confidence interval for the difference of 0.007 – 0.012mm, this yields an upper limit of approximately +1.6% for the μ CT-induced thickness bias (0.012mm/0.753mm).

3.2 μ CT to CT Bone Surface Registration

Fit of the μ CT-generated bone surfaces to the clinical CT-generated bone models was quite good, even though there were statistically significant differences in bone volume, centroid location, and inertial axis orientation for each bone (Table 2). On average, the μ CT-generated bone volumes were $8.51 \pm 4.95\%$ larger than the clinical CT-generated bone volumes (9.80%, 6.70% and 9.03% for the scaphoid, lunate and capitate bones, respectively), and their surfaces fell an average of 0.36 ± 0.10 mm outside of the CT-generated bone surfaces. However, positive and negative non-congruent regions were evenly distributed across the bone surfaces, suggesting there was little, if any, systematic bias (Figure 3). The overall (n=21) average difference between the bone centroid locations was 0.33 ± 0.16 mm, with an upper (97.5%) confidence limit of ~ 0.55 mm in any one direction. The overall (n=63) average angle between the μ CT and clinical CT-generated inertial axes was 2.42 ± 1.56 degrees, with an upper (97.5%) confidence limit of ~ 5.5 degrees for any one axis.

4. Discussion

In this paper we present a method for generating 3-D models of articular cartilage from μ CT images, as well as estimates of edge detection and registration accuracy. Our approach involves simple segmentation of the cartilage surfaces from 3-D image datasets, and registration to pre-existing bone models using transforms generated via surface fitting algorithms in *geomagic*® *QUALIFY*®. Our data indicate that the methodology generate cartilage thickness maps accurate to within $\sim 1.6\%$ of actual cartilage thickness, and register them to CT-generated bone models to within ~ 0.33 mm and ~ 2.5 degrees on average (97.5% confidence limits of 0.55 mm and 5.5 degrees, respectively).

We used a 2-D approach to validate our μ CT-derived cartilage thickness values because it provided a simple method for one-to-one comparison of μ CT and full-size image data, while limiting the risk of tissue processing artifacts. We are unaware of a comparably robust methodology for 3-D comparisons. The errors in our cartilage thickness values were on the order of our μ CT imaging resolution ($\sim 10\mu\text{m}$). The use of lower-resolution μ CT imaging techniques will undoubtedly reduce accuracy. Accordingly, error estimates should be calculated on a case-by-case basis for alternate imaging protocols.

We fit the μ CT-generated bone surfaces, which are the inner cartilage surfaces, to the corresponding CT-generated bone models utilized a least-squares surface fitting algorithm in *geomagic*® *QUALIFY*®. We chose a surface fitting strategy over centroid and inertia registration, as surface fitting has been shown to be more robust in kinematic accuracy studies (Neu et al., 2000). Our localization of the centroids to within ~ 0.33 mm (97.5% confidence limit 0.55 mm) and inertia axes to within ~ 2.5 degrees (97.5% confidence limits of 5.5 degrees) are very consistent with reported kinematic errors of ~ 1.0 mm in translation and ~ 2.0 degrees in rotation associated with similar techniques (Neu et al., 2000).

At this point the technique is most applicable to subject-specific models driven using kinematic data obtained through in vitro testing. Ultimately, it may be possible to generate a family of cartilage surfaces that could be scaled and/or morphed for application to models from live subjects and in vivo kinematic data. In that case it would be possible to analyze cartilage contact in the normal wrist, as well as in cases of pathology and therapeutic intervention (i.e. surgery).

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Figure 1. Volar (L) and dorsal (R) view of μ CT-generated cartilage surfaces (red) applied to CT-generated carpal bone models (gray). The cartilage surfaces were registered to the bones using transforms obtained via fitting of μ CT-generated bone surfaces to CT-generated bone surfaces.

Figure 2.

Scheme for processing the flatbed and μ CT images for cartilage surface comparison. Raw 2-D images were binarized and the inner and outer cartilage contours were generated using commercially available image processing software. The accuracy of the μ CT-generated contours was assessed via direct comparison to contours generated from the flatbed images.

Figure 3. Typical false-color representation of the distance (in mm) between the μ CT and CT-generated bone surfaces from a capitate bone. The light blue/yellow mottled appearance indicates that distances between the two surfaces were small, and that the differences (positive or negative) were essentially randomly distributed.

Comparison of cartilage thicknesses determined from μ CT slice and flatbed scanned images, for one scaphoid (Sca), one lunate (Lun), one trapezoid (Tpd), and two Triquetrum bones (Tqm1 and Tqm2). Note: For the purposes of this analysis, cartilage thickness was defined as the distance between the inner and outer cartilage surfaces along a radial line from the geometric center of the co-registered point clouds.

Table 1

Bone Slice	* n	Thd.	Cartilage Thickness (mm)		Difference (mm)	p value	95% C.I.
			Flatbed ($\mu \pm \text{std. dev.}$)	μ CT ($\mu \pm \text{std. dev.}$)			
Sca	133	610	0.838 $\pm$ 0.149	0.847 $\pm$ 0.174	0.009 $\pm$ 0.003	0.004	0.003 – 0.015
Lun	160	640	0.847 $\pm$ 0.155	0.855 $\pm$ 0.136	0.008 $\pm$ 0.003	0.008	0.002 – 0.013
Tpd	103	633	0.656 $\pm$ 0.148	0.658 $\pm$ 0.163	0.002 $\pm$ 0.004	0.659	-0.005 – 0.009
Tqm1	189	600	0.719 $\pm$ 0.127	0.717 $\pm$ 0.119	-0.002 $\pm$ 0.003	0.448	-0.007 – 0.003
Tqm2	113	622	0.681 $\pm$ 0.168	0.712 $\pm$ 0.715	0.031 $\pm$ 0.003	<0.001	0.024 – 0.038

* n = # of points and degrees of cartilage coverage for each bone slice
 Thd. = Threshold value (Scale 0 - 1,000)
 std. dev. = standard deviation
 s.e.m. = Standard Error of the Mean

Table 2

Comparison of bone volumes, centroid locations, and inertial axis orientations for scaphoid (Sca), Lunate (Lun) and capitate (Cap) bone surfaces generated clincial CT scans of the intact wrist and μ CT scans of the individually explanted bones.

		Bone Volume (mm ³)			Distance Between Bone Centroids (mm)		Angle Between CT and μ CT Inertial Axes (degrees)			
Bone	n	CT ($\mu \pm \sigma$)	μ CT ($\mu \pm \sigma$)	p value	μ CT-CT (95% CI)	p value	1 (95% CI)	2 (95% CI)	3 (95% CI)	p values (Axis 1, 2, 3)
Sea	7	2,900 ($\pm 1,193$)	2,597 ($\pm 1,019$)	0.027	0.31 (0.10 – 0.54)	0.003	1.96 (0.29 – 4.11)	2.64 (–0.39 – 5.30)	2.92 (–0.99 – 5.54)	(0.018, 0.030, 0.062)
Lun	7	1,990 (± 546)	1,776 (± 451)	<0.001	0.35 (0.16 – 0.55)	0.001	2.17 (0.27 – 4.06)	2.74 (0.82 – 4.67)	2.40 (0.24 – 4.55)	(0.018, <0.001, 0.021)
Cap	7	3,524 ($\pm 1,106$)	3,308 (± 927)	<0.002	0.32 (0.10 – 0.52)	0.003	2.20 (0.96 – 2.97)	2.74 (1.57 – 3.70)	2.28 (1.87 – 3.97)	(0.002, <0.001, <0.001)

μ CT = Micro-computed tomography (60 μm isometric voxel resolution)

CT = Clinical computed tomography (0.3mm $\times$ 0.3mm in-plane resolution, 1.0mm along the z axis)