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Short communication

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 $\sim$1.6% of the cartilage thickness. Registration error averaged 0.33 ± 0.16 mm (97.5% confidence limit of $\sim$0.55 mm in any one direction) and $2.42 \pm 1.56^{\circ}$ (97.5% confidence limit of $\sim 5.5^{\circ}$ in any 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 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 (μCT) 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 (Fig. 1), which can then be coupled with in vitro kinematic data (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 μCT-generated cartilage facets to the CT-generated bone models.

2. Methods

2.1. Methodology overview

Disarticulated carpal bones are μCT 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 μCT 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 (2.2) and registration (2.3) sections, below.)

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