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High resolution bone material property assignment yields robust subject specific finite element models of complex thin bone structures

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ABSTRACT

Accurate finite element (FE) modeling of complex skeletal anatomy requires high resolution in both meshing and the heterogeneous mapping of material properties onto the generated mesh. This study introduces Node-based elastic Modulus Assignment with Partial-volume correction (NMAP) as a new approach for FE material property assignment to thin bone structures. The NMAP approach incorporates point spread function based deblurring of CT images, partial-volume correction of CT image voxel intensities and anisotropic interpolation and mapping of CT intensity assignment to FE mesh nodes. The NMAP procedure combined with a derived craniomaxillo-facial skeleton (CMFS) specific density-isotropic elastic modulus relationship was applied to produce specimen-specific FE models of 6 cadaveric heads. The NMAP procedure successfully generated models of the complex thin bone structures with surface elastic moduli reflective of cortical bone material properties. The specimen-specific CMFS FE models were able to accurately predict experimental strains measured under *in vitro* temporalis and masseter muscle loading ($r=0.93$, slope$=1.01$, $n=5$). The strength of this correlation represents a robust validation for CMFS FE modeling that can be used to better understand load transfer in this complex musculoskeletal system. The developed methodology offers a systematic process-flow able to address the complexity of the CMFS that can be further applied to create high-fidelity models of any musculoskeletal anatomy.

1. Introduction

The most basic skeletal finite element (FE) models use homogeneous or limited heterogeneous segmentations to define bone material properties (Zannoni et al., 1998). Validated subject-specific state-of-the-art FE studies have established that accurate skeletal models require both high resolution in meshing and heterogeneous material property mapping (Helgason et al., 2008b; Taddei et al., 2006; Schileo et al., 2007). Hounsfield units in a density calibrated computed tomography (CT) scanner can be correlated to bone mineral density values, followed by transformation to empirically derived elastic modulus values (Zannoni et al., 1998; Morgan et al., 2003; Keller, 1994; Dalstra et al., 1993; Carter and Hayes, 1977; Helgason et al., 2008a; Zioupos et al., 2008). The specific mathematical relationship between density and modulus has been shown to be dependent on anatomical site and the density regime (cortical versus trabecular), however investigators have arrived at very different results even for bones of a single site and species (Schileo et al., 2007). This may be due to non-standard methods of measuring density and variable definitions of bone density, compounded by correlations used to convert from one definition to the other. Care must be taken in using extrapolations of phantom based measurements that relate trabecular intensity to density via linear interpolation and experimentally measured density to modulus correlations outside of experimentally validated bone density ranges. For density to modulus conversions specific to the craniomaxillo-facial skeleton (CMFS), Peterson et al. (Peterson and Dechow, 2003; Peterson et al., 2006) mapped the outer cortical table of the CMFS reporting regional anisotropic elastic properties, but the data set is too sparse to permit anisotropic mapping of elastic properties for a continuum CMFS mesh.

In long-bone skeletal biomechanics, the BONEMAT method has been most widely adopted and validated for subject-specific FE modeling (Viceconti et al., 2004; Poelert et al., 2012). This algorithm

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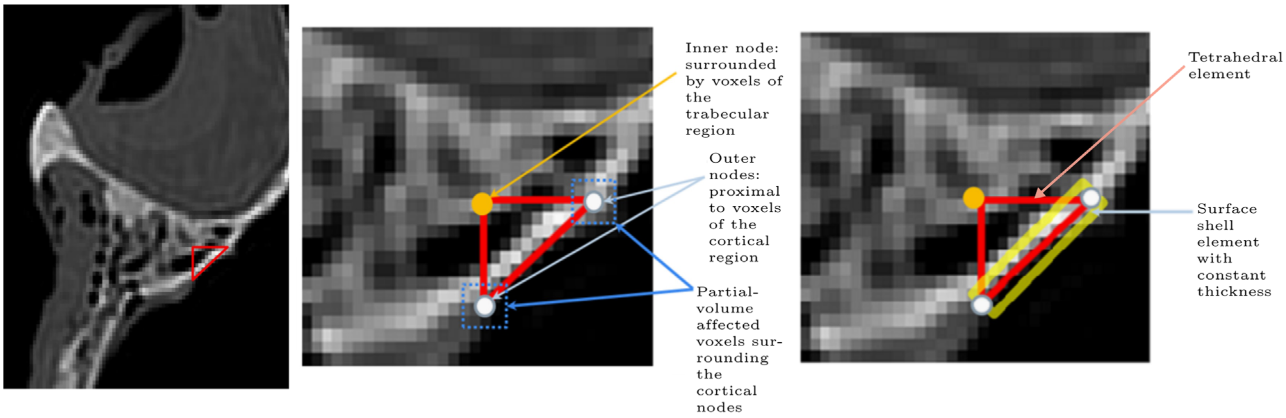
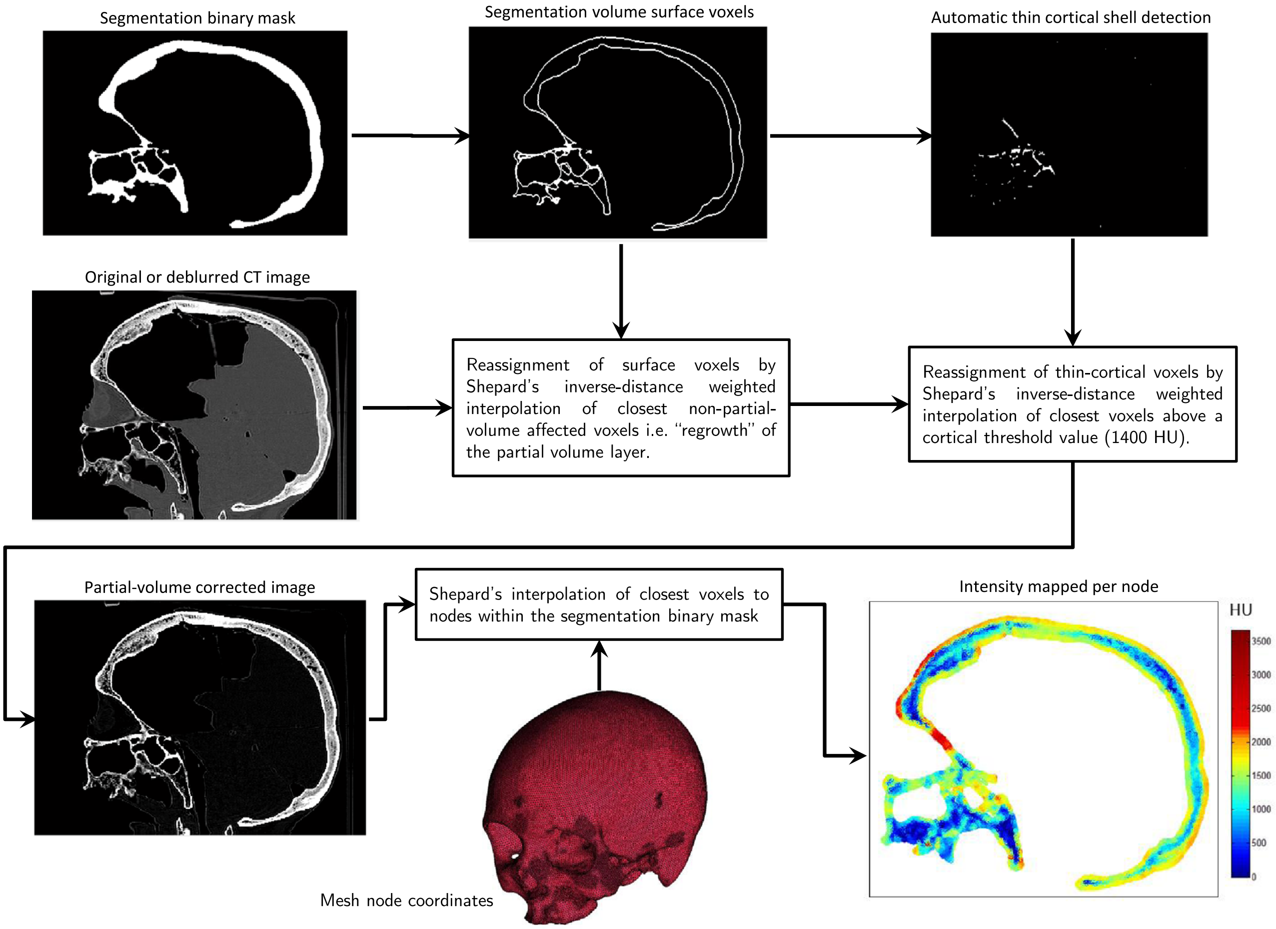


Fig. 1. An axial slice in the zygoma region. A cross-section of a tetrahedral element is shown. Close up of the element illustrates coordination of the nodes with the voxels on the CT images (middle) and the shell element approach for modeling of thin-bone structures (right).



Reassignment of surface voxels by Shepard's inverse-distance weighted interpolation of closest non-partial-volume affected voxels i.e. "regrowth" of the partial volume layer.

Reassignment of thin-cortical voxels by Shepard's inverse-distance weighted interpolation of closest voxels above a cortical threshold value (1400 HU).

Shepard's interpolation of closest voxels to nodes within the segmentation binary mask

Fig. 2. The process flow for the NMAP PV correction of segmented CT images, with specific measures for enforcing non-PV interpolation in thin compact bone regions.

interpolates the intensity of the voxels mapped from the CT image to the volume of the elements of the FE mesh, assigning an elastic modulus to each individual element. Alternatively, voxels mapped to the vicinity of the nodes of each element can be assigned individual values (Helgason et al., 2008b). However, both surface nodes and elements may lie within regions which are corrupted by partial-volume (PV) effects. PV effects result in "blurring" of intensity values at boundaries with sharp intensity transitions, where the imaging system's resolution is unable to resolve the outline of thin, high-intensity structures (Ionescu et al., 2011). As shown in Fig. 1, materials of heterogenous intensities (from air to cortical bone) may be enclosed by a single element. The element's density, if calculated by averaging the enclosed voxels, results in a value equivalent to soft-tissue or low apparent density trabecular bone. To overcome this issue, some authors employ shell elements at the surface (Fig. 1, right), however, this simplification does not address the inability to sample and map the regional cortical bone density values on the FE mesh surfaces (Szwedowski et al., 2011; Anderson et al., 2005; Gupta et al., 2004).

Recent work has described the use of deblurring algorithms to reconstruct geometry and intensity values in CT data of skeletal structures (Pakdel et al., 2012, 2014). Deconvolution using a point spread function (PSF) has been shown to yield significant improvements in