3D Geodesic Topological Analysis of Trabecular Bone Micro-Architecture of the Proximal Femur

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Introduction. Osteoporosis has been defined by NIH as a skeletal disorder characterized by compromised bone strength predisposing to an increased risk of fracture. The proximal femur is the anatomical site where most of the fractures leading to morbidity and mortality occur, however due to its deep-seated location in the human body is also among the most difficult to study in-vivo. Currently, due to recent advances in hardware, pulse sequence development and coil design, MRI is the only imaging modality capable of offering in-vivo high-spatial resolution (HR) images to quantify trabecular bone micro-architecture of the proximal femur. Geodesic Topological Analysis (GTA) is a trabecular bone analysis technique that quantifies the trabecular bone network in terms of its junctions providing composite measures of scale, topology, and anisotropy [1]. Although GTA has shown its potential in a fracture discrimination study [1], GTA has been limited to its 2D implementation. The purpose of this work was then twofold: 1) to develop a technique to perform 3D GTA; 2) to demonstrate 3D GTA on HR-MR images of the proximal femur.

Materials and Methods. Digital phantoms of intersecting plates with rods simulating components of a trabecular bone network were created for validation purposes (Fig. 1). In-vivo coronal HR-MR images of the proximal femur were acquired to demonstrate the in-vivo application of 3D GTA (Fig. 2). Images were acquired on a 3 Tesla MR750 scanner (GE Medical Systems) using an 8 channel phased-array coil and a 3D fully-balanced steady-state free-precession pulse sequence with two phase-cycled acquisitions. Acquisition parameters included a TR of 8.6ms, flip angle of 60°, TE of 3.0ms, FOV of 120mmx120mmx50mm, and matrix size of 512x384x100 (Frequency x Phase x Slices) for a final spatial resolution of 0.234mmx0.234mmx0.5mm after reconstruction, yielding an acquisition time of 13 minutes and 19 seconds. MR images were coil corrected using nonparametric non-uniform intensity normalization (N3) [2], and cylindrical volumes of interest (VOI) of 5mm radius and 5mm height were manually defined at the head, neck and trochanteric regions (Fig. 2). VOI were segmented using Bone-Enhancement Fuzzy C-Means (BE-FCM) clustering [3] to compute fuzzy bone volume fraction (f-BVF) maps. BE-FCM clustering uses partial membership segmentation and in addition to voxel intensities incorporates local second order features for bone enhancement at multiple scales. This approach is meant to allow for a soft segmentation that accounts for partial volume effects while suppressing the influence of noise. Cubic interpolation was then applied to the f-BVF maps to obtain maps with isotropic spatial resolution (0.234mm). Interpolation was applied to the f-BVF maps and not directly to the N3-coil-corrected images to increase robustness to noise. Isotropic f-BVF maps were thresholded at 0.5 to obtain a binary representation of the trabecular bone networks.

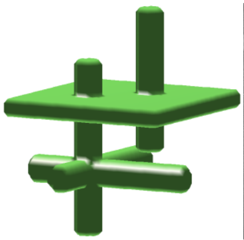

Fig 1. Digital phantom.

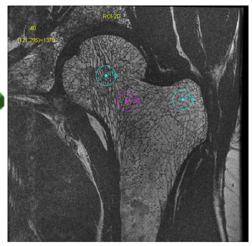

Fig 2. HR-MR image.

An essential component of GTA is junction identification which requires skeletonization of the trabecular bone network. Skeletonization of digital phantoms and isotropic-binarized f-BVF maps was performed using MB-3D [4], which is a fully parallel, shape-preserving, and homotopic thinning algorithm, followed by CE-3D [5] to yield one-voxel thick skeletons. Topological classification (TPC) of each skeleton voxel was performed based on topological numbers [6], a technique that classifies each voxel into 1 out of 9 categories: 1) interior point, 2) isolated point, 3) edge point, 4) curve point, 5) curve-curve junction, 6) surface point, 7) surface-curve junction, 8) surface-surface junction, 9) surfaces-curve junction. A tenth category was created from edge points: curve end.

Based on minimum Euclidean geodesic distances, which are defined as the shortest path between two points, each voxel in the isotropic-binarized f-BVF was assigned to its closest connected junction. This assignment has the assumption that the relationship of a particular bone element is stronger to its closest connected junction than to any other junction in the network. The trabecular bone architecture can then be broken down into groups of voxels belonging to different junctions enabling the quantification of individual junctions, junctions with their group of assigned voxels, as well as the interrelationship between junctions. In the 2D implementation of GTA, a total of 7 apparent trabecular bone parameters that quantify the spatial distribution of trabecular bone in terms of its volume, spacing, and orientation were created. Two parameters quantify the trabecular bone volume: volume of junction (VJ; mm^3) and convex hull of junction (CHJ; mm^3); two the trabecular bone spacing: junction spacing (JSp; mm) and distance to junction (DJ; mm); and three the trabecular bone orientation: junction eccentricity (JE; unitless), junction orientation (JO; unitless), and inter-junction orientation (IJO; unitless). In this work, due to space constraints only VJ and JSp results will be presented.

Results. Skeletonization results of a digital phantom are shown in Fig. 3. In this figure, preservation of shape and topology can be appreciated along with the medial location of the skeleton. 3D GTA results are shown in Fig. 4 for both the digital phantom and an in-vivo example. As can be observed in Fig. 4, by applying a similar approach of minimum geodesic distances between the volume and the TPC of its skeleton, a classification of rods and plates can be obtained for each voxel.

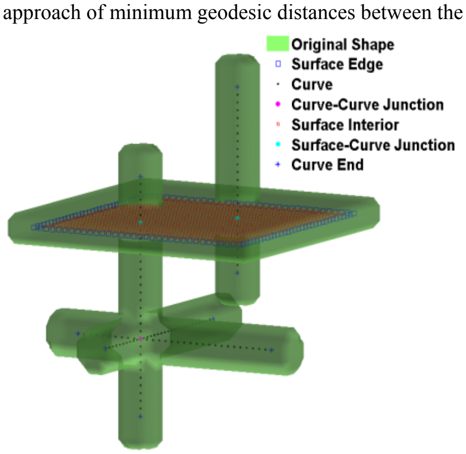

Figure 3. Digital phantom, its skeleton and TPC.

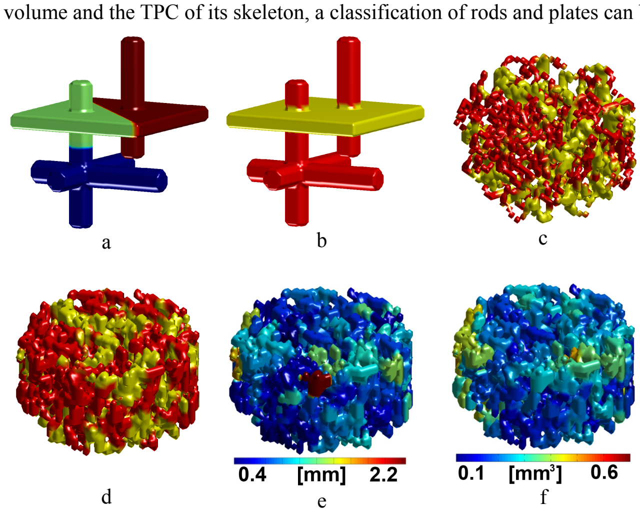

Figure 4.
Digital phantom:
a) Junction map. Voxels assigned to the same junction share the same color.
b) Classification of plates (yellow) and rods (red).
Neck VOI:
c) Skeleton with classification of plates (yellow) and rods (red).
d) Classification of plates (yellow) and rods (red).
e) JSp map. Voxels were assigned the same spacing value of their closest connected junctions.
f) VJ map. Voxels were assigned the same fuzzy volume value of their closest connected junction.

Conclusions. In this work we have presented a set of image processing algorithms to perform 3D GTA. The technique has been validated with known shapes by using digital phantoms, and its application to in-vivo HR-MR images of the proximal femur has been demonstrated. We are currently investigating the discriminatory power of the above analysis in the proximal femur to distinguish between subjects with and without osteoporotic fractures.

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References. [1] Carballido-Gamio et al., Magn Reson Med. 2009;61(2):448-56. [2] Folkesson et al. Med Phys. 2009 Apr;36(4):1267-74. [3] Folkesson et al. Med Phys. 2010 Jan;37(1):295-302. [4] Manzanera et al. IEEE ICCV. 1999; 337–43. [5] Stauber et al. Bone. 2006;38(4):475-84. [6] Malandain et al. IJCV. 1993;10(2):183-197.