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Topology Optimization-based Bone Microstructure Reconstruction from CT Scan Data

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ABSTRACT

For osteoporosis diagnosis, bone microstructure is considered as the most reliable measure of bone strength. However, there exist significant difficulties in representing *in vivo* bone microstructure due to the limited spatial resolutions of current clinical imaging devices such as CT and MRI. This study presents a novel method that can reconstruct bone microstructures from CT scan data, using the finite element analysis and topology optimization. Based on Wolff's law which states the self-optimizing capabilities of bone, topology optimization for compliance minimization is performed to reconstruct trabecular microarchitecture in the VOIs. A constraint for the BMD deviation is involved to maintain the patient-specific spatial bone distribution obtained from the quantitative CT (QCT) scan data. By doing so, the proposed method can enhance the QCT images of a 625μm resolution up to those of a 62.5μm resolution, which can precisely represent bone microstructure. Numerical results indicate that, by reconstructing bone microstructure, the proposed method can contribute to improving the accuracy of bone strength assessment and, therefore, can be a valuable tool for early osteoporosis diagnosis in the clinical field.

1. INTRODUCTION

Both resolution and dimensionality of skeletal images are significant factors for reliable diagnosis of bone health because higher resolution clinical images in 3D allow for more accurate bone strength assessments. Areal bone mineral density-based assessments using 2D low-resolution (LR) images comprise only 60–75% of the bone strength, therefore often leading to misdiagnoses (Gafni and Baron 2004). In contrast, bone microstructure-based assessments using 3D high-resolution (HR) images can predict up to 94% of the bone strength (Goldstein et al. 1993). Thus, 3D HR imaging

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techniques for bone microstructures have been in great demand in the clinical field.

Although the current CT scanners have an increased number of detectors with reduced sizes, they require excessive radiation doses in order to achieve HR images. The aforementioned difficulty has forced many researchers to use micro CT for cadavers (Verhulp et al. 2008) to acquire HR skeletal images. In principle, a trabecular bone is the result of a bone remodeling process that reorients the trabeculae to obtain the maximum mechanical efficiency while preserving the minimum bone mass (Wolff 1892). This implies that the trabecular architecture can be reconstructed through simulating this metabolic process. For example, the trabecular architecture in the proximal femur (Jang and Kim, 2009, 2008; Lee et al. 2015) and lumbar spine (Jang and Kim 2010) were successfully reconstructed in 2D using topology optimization. Inspired by these findings, Kim and Jang (2016) recently proposed a new resolution enhancement method that can reconstruct a 50μm-resolution trabecular architecture from a 600μm-resolution synthetic input image of a proximal femur through conducting topology optimization. Although the research demonstrated the feasibility of topology optimization-based resolution enhancement using a 2D synthetic femur, more thorough validation should be conducted for clinical applications using clinical scan data.

This study presents a novel method that can reconstruct bone microstructures from CT scan data, using the finite element analysis and topology optimization. After segmenting the target bone from the scan data, a localized finite element (FE) model is constructed through determining the physiological local loads for the volume of interest (VOI) to save the computing cost. In the topology optimization, multi-resolution bone mineral density (BMD) deviation constraints and a black-and-white filtering constraint are imposed to improve the convergence and image quality. The proposed method reconstructs the trabecular architecture in the VOIs from the LR scan data while preserving the patient-specific spatial BMD distribution. Numerical results demonstrate the clinical feasibility of the proposed method for resolution enhancement.

2. PROPOSED METHOD

From the CT scan data, a 3D target bone was segmented using the complementary relationship between the watershed algorithm and optimal thresholding (Kim et al. 2018). This scheme can preserve the thin cortical bone and trabecular compartment during the image segmentation despite the low resolution and noise of the original images. Then, the segmented skeletal image was converted to a relative density map, which has a range of 0.01 to 1, through linear scaling between the minimum and maximum voxel values.

To reduce the computational burden in the FE analysis, a localized FE model for the VOI was constructed from the segmented skeletal image through determining and imposing the physiological local loads around the VOI (Kim et al. 2016). Each voxel in the VOI was converted to an 8-node brick element, of which the elastic modulus was estimated using the rescaled modulus-density relationship (Kim and Jang 2016).

Poisson's ratio of 0.3 was used for all finite elements. Then, resolution upscaling was conducted in the localized FE model, in which each voxel of the clinical scan data was divided into n × n × n subvoxels while preserving the original voxel value. Depending on the clinical and target resolutions, the appropriate division (n) can be determined in order to precisely represent the trabecular morphology. To effectively reconstruct a 3D bone microstructure in the upscaled resolution, the relative density of each voxel was converted to its own elastic modulus, as follows:

$$E(\rho_{(r,s,t)}) = \rho_{(r,s,t)}{}^{\gamma} E_0 \tag{1}$$

where $\rho_{(r,\,s,\,t)}$ denotes the relative density of the voxel at (r, s, t) in the upscaled image; E_0 is the reference elastic modulus of the trabecular bone, and γ is the penalization exponent. Thus, the trabecular structure can be reconstructed through assigning appropriate values of $\rho_{(r,\,s,\,t)}$ to each voxel as a result of topology optimization.

For topology optimization, the design variables were the relative densities in the upscaled resolution, of which the total number is the same as the number of finite elements used in the localized FE model. The minimization of compliance (i.e. maximization of stiffness) was set as an objective function in order to reflect Wolff's law. The multi-resolution BMD deviation constraints, which can be derived from the original scan data, were imposed at multiple downscaled resolutions to effectively preserve the patient-specific bone spatial distributions. A black-and-white filtering constraint was also imposed in order to achieve clearer images through penalizing the intermediate relative densities. Thus, the proposed resolution enhancement can be formulated as follows:

$$\begin{aligned} &\textit{Minimize} && f(\boldsymbol{\rho}) = \sum_{l=1}^{L} c_l \left(\frac{1}{2}\mathbf{u}_l^T \mathbf{K} \mathbf{u}_l\right) \\ &\textit{Subject to} && g_m(\boldsymbol{\rho}) = \frac{1}{N_m}\left\| \boldsymbol{\rho}^{(\mathrm{m})} - \boldsymbol{\rho}_0^{(m)} \right\|^2 \le \varepsilon_1 \quad (m = 1, 2, \cdots M) \\ & && g_{M+1}(\boldsymbol{\rho}) = \frac{1}{N}\sum_r \sum_s \sum_t \rho_{(r,s,t)} \left(1 - \rho_{(r,s,t)}\right) \le \varepsilon_2 \end{aligned} \tag{2}$$

where $\boldsymbol{\rho}$ denotes the relative density tensor of a reconstructed image at the target resolution in the VOI, and $\boldsymbol{\rho}^{(\mathrm{m})}$ are $\boldsymbol{\rho}_0{}^{(\mathrm{m})}$ the downscaled relative density tensors of the reconstructed and reference images, respectively, at the resolution of level m; c_l is the weighting factor for the lth load case; $\mathbf{u}_l$ is the displacement vector for the lth load case; $\mathbf{K}$ is the stiffness matrix of the upscaled FE model for the VOI; ε_1 and ε_2 are small constant values, and N_m is the total number of finite elements at the resolution of level m. Note that the localized FE models for the VOIs consisted of 1728 elements, whereas the full FE model for the proximal femur consisted of 454,567 elements.

To investigate the clinical applicability of the proposed method, the CT scan data of a 62-year-old female was used. Four VOIs were selected in the femoral head, femoral neck, Ward's triangle, and intertrochanteric region, all of which are well known to include the representative trabecular patterns (Fig. 1).

3. RESULTS

Figure 1 presents the original CT scan data (input data) and the corresponding enhanced HR images (output data) for the VOIs. Unlike the CT scan data, the enhanced images clearly depict the characteristic trabecular patterns: the plate-like trabecular architecture that is aligned along the hip joint load (femoral head); a mixture of both plate-like and rod-like trabecular architectures (femoral neck); rod-like trabeculae that are fewer and thinner than those in other VOIs (Ward's triangle); and trabecular patterns that have mutually orthogonal intersections (intertrochanter).

Table 1 indicates that the trabecular morphometric indices of the enhanced HR images. The structure model index (SMI) of the femoral head is 0.84, which signifies the plate-like trabecular architecture. Conversely, the SMI values of the Ward's triangle and intertrochanter (2.79 and 2.48, respectively) indicate a rod-like trabecular architecture in the two VOIs. The femoral head has the highest BV/TV, whereas the Ward's triangle has the lowest BV/TV.

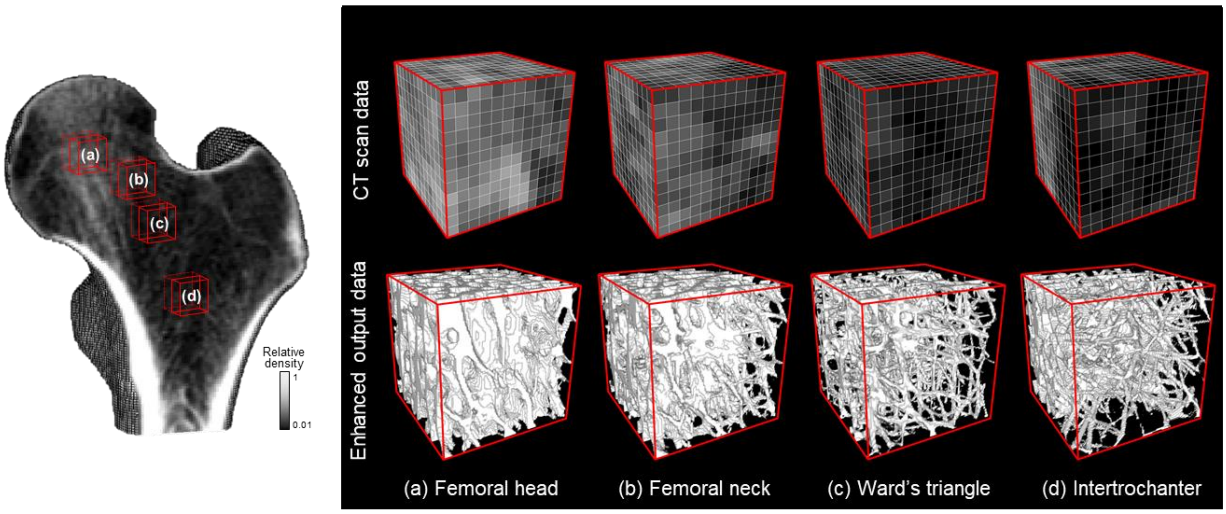

Fig. 1 Comparison of the original CT scan data and the HR output data for the four VOIs in the proximal femur

Table 1 Trabecular morphometric indices obtained from the enhanced HR images

Index	Femoral head	Femoral neck	Ward's triangle	Intertrochanter
BV/TV (%)	0.29	0.18	0.09	0.13
Tb.Th (mm)	0.24	0.21	0.16	0.20
Tb.Sp (mm^{-1})	0.65	0.73	0.97	0.84
SMI (-)	0.84	1.86	2.79	2.48

4. CONCLUSIONS

This study proposed a resolution enhancement method through localizing the volume of interest from the clinical scan data and implementing the multi-resolution BMD deviation constraints in the topology optimization. A case study with the clinical CT scan data demonstrated the feasibility and applicability of the proposed resolution enhancement for further clinical applications.

The current clinical imaging modalities such as CT and MRI have a limited spatial resolution of approximately 600 μm due to the radiation doses, SNRs, and/or scan times. Therefore, with further work, the proposed method could become a key technique to provide HR skeletal images of 50–100 μm resolution for more accurate diagnoses of bone status, thus opening an era of personalized medicine in skeletal imaging.

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