LIMITATIONS OF HOMOGENIZED FINITE ELEMENTS ANALYSIS OF DISTAL TIBIA SECTIONS

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Introduction

High-resolution peripheral quantitative computed tomography (HR-pQCT) based homogenized finite element (hFE) analysis allows accurate prediction of stiffness and strength of the distal radius and tibia [1]. Despite the capacity of hFE to predict structural properties, it remains unclear if the homogenization scheme is able to capture high-strain localizations i.e. actual fracture zones [2]. Therefore, the objective of this study is to investigate the compressive post-yield behavior of the distal tibia and to compare hFE predictions with experimental tests by both qualitative and quantitative means.

Methods

Twenty-five fresh frozen anatomic specimens of human tibiae were used in this study. A 3 cm (3 stacks) distal section was scanned by HR-pQCT (XCT II, Scanco Medical, Switzerland). Then, sections were cut out as close as possible to the HR-pQCT triple stacks, lapped, and scanned in a µCT with a 24.5 µm voxel size. The sections were tested in compression up to failure and scanned again in µCT. The scans were then downscaled to 72.5 µm voxel size, similar to HR-pQCT resolution. hFE analysis was performed in order to reproduce the plastic deformation field resulting from the compressive experiment as closely as possible. On the other hand, registration between post- and pre-experiment scans was performed in two steps: 1) rigid registration, and 2) b-spline registration. Quantitative 3D registration assessment was performed using the Dice coefficient. The deformation gradient (**F**) was extracted in both hFE and registration. Then, volumetric deformation (det**F**) and the norm of isovolumic deformation ($\|\tilde{\mathbf{F}}\|$) were obtained using the unimodular decomposition of **F** (equ. 1). Finally, a qualitative assessment was performed by looking at the mid-slice of rigid and b-spline registration, and **F** resulting from both the registration and the hFE simulation.

$$\mathbf{F} = \det(\mathbf{F})^{-1/3}\,\tilde{\mathbf{F}} \qquad (1)$$

Results

Structural parameters showed good agreement between the experiment and hFE both for stiffness (R^2=0.89, slope=0.96 with 95% CI [0.82, 1.11]) and ultimate force (R^2=0.97, slope=1.04 [0.95, 1.12]). The quantitative assessment showed a moderate increase of the mean Dice coefficient from 0.57 (rigid registration) to 0.62 (b-spline registration). The qualitative assessment of hFE sections allowed the classification of the samples into 3 categories: bad (14 sections), semi (6), and good agreement (5).

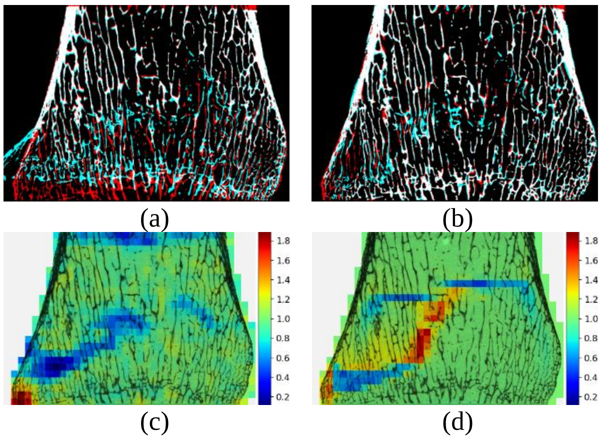

Figure 1: Example of a section presenting semi-agreement between registration and hFE. (a) Rigid registration with red: initial section, cyan: failed section, and white: superimposition of both. (b) b-spline registration with the same color code. (c) detF resulting from registration. (d) detF resulting from hFE.

Discussion

The good correlations between hFE and experiment for structural parameters are similar to previous studies [1]. The qualitative assessment of the plastic deformation field is acceptable for registration but not for hFE. The failure zones determined by hFE correspond to registration only in 20% of the cases. We attribute these discrepancies to local elastic/plastic buckling effects that are not caught by our continuum-based FE approach exempt of strain softening. To conclude, the used hFE scheme captures reliably the elastic and yield response of the bone sections but not the subsequent failure process.

References

[1] Schenk et al, J Mech Behav Biomed Mater, 131, 2022.
[2] Varga et al, J Biomech, 42, 2009.

Acknowledgements

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