Validation of local displacement predictions of MicroFE models of trabecular bone and vertebral bodies by Digital Volume Correlation

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Introduction

The digital volume correlation (DVC) approach, combined with micro-computed tomography (microCT) imaging of undeformed and deformed specimens, can be used to study the 3D heterogeneous distribution of displacements and strain in loaded bone structures [1]. This is essential for studying the relationship between local morphometric, densitometric and mechanical properties of bone and the associated bone remodeling process, fundamental to optimize the design of implants or biomaterials. Moreover, DVC outputs can be used to validate microCT based finite element (microFE) models [2] that can predict the local strains and stresses of the complex bone structure under different loading scenarios. While so far these models have been validated for predictions of structural apparent stiffness [3], little is known about their ability of predicting local material properties. For example Zauel et al. [4] shows that microFE models of trabecular bone specimens can predict accurately displacements along the loading directions but are less accurate in predicting those in the transverse directions. As there is no reason for anisotropic behaviour of both DVC measurements and MicroFE predictions, this result is rather surprising. We have recently developed a DVC approach that has higher precision than the others reported in the literature [5]. Moreover, little is known about the prediction of local properties by microFE models applied to whole organs, as the vertebral body. The aim of this study was to test the ability of microFE models in predicting local displacements by using state of the art DVC approach at two dimensional levels: single trabecular bone specimens and whole vertebral bodies.

Methods

Two sets of validation studies were performed to test the prediction ability of microFE models of trabecular bone specimens or whole vertebral bodies. A trabecular bone specimens (8mm in nominal diameter and 12mm in nominal length) was extracted from the greater trochanter of a bovine femur [6]. The second set consisted of porcine vertebral bodies, where the posterior element was removed (N=4). All specimens were collected from animals destined to alimentary purposes and were mechanically compressed in the elastic range within a microCT scanning device. The trabecular bone specimen was scanned (Skyscan1172, Bruker) with a voxel size of ~10μm and the images were resampled to ~20μm for reducing the computation time of DVC and microFE. The vertebral bodies were scanned (XTH225, Nikon) with a voxel size of ~40μm. Each couple of undeformed and deformed images was elastically registered with a global DVC approach based on the Sheffield Image Registration toolkit combined with a finite element software package (ShIRT-FE). Previous studies identified the best registration setting parameters to obtain low experimental uncertainties for displacement measurements [5, 7]. Grids with nodal spacing equal to ~500μm (for trabecular bone) and to ~1900μm (for vertebral bodies) were used. Each undeformed image was binarized according to the frequency distribution of the grey-values and each bone voxel was converted into linear hexahedral elements with isotropic material properties (Young's modulus equal to 17GPa, Poisson ratio equal to 0.3). The boundary conditions in the microFE models were assigned according to the interpolated DVC measurements [4]. The predicted and measured displacements were compared in the location of the DVC nodes, which fell within the middle portion of the specimens and within the bone tissue. Linear regressions were calculated and slope, intercept (Int), coefficient of determination (R^2) and root mean square error percentile (RMSE%) were calculated for each specimen for both bone types.

Results

The microFE showed excellent predictions of local displacements in all three directions, for both specimen types and for each specimen, with regressions close to the 1:1 relationship (slopes between 0.85 and 1.11; intercepts between -34 and 21 μm), R^2 close to 1 (between 0.89 and 0.99) and RMSE% below 5.6% (Figure1).

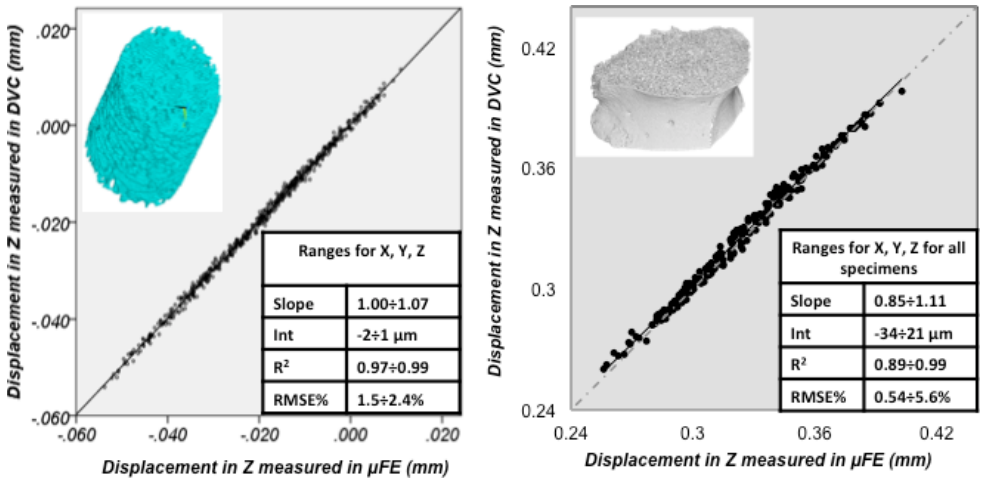

Figure 1: *Correlation between the displacement along the loading direction measured with DVC and predicted by microFE models for the trabecular bone sample (left) and a typical vertebral body (right). In the tables ranges of the statistical parameters for every direction and every specimen are reported.*

Discussion

The results of this study confirmed that microFE models based on microCT images of bone are capable of accurately predict the local displacements along the three directions for analyses performed at the tissue and organ dimensional levels. The only other attempt to quantitatively validate microFE models of trabecular bone with a DVC method [5] showed good predictions only along the loading directions, probably due to issues related to the DVC or modelling methodologies. Considering that bone remodelling and failure are thought to be regulated by local strains, it would be preferable to validate the microFE models in terms of strain predictions. However, so far the DVC approaches are not precise enough to allow proper validation with a spatial resolution of 20-40μm, unless higher resolution Synchrotron imaging is used [8]. Considering that this approach is currently invasive and affects the mechanical properties of the tissue tested *in situ*, further research on this topic needs to be done.

The main limitation of this study it the low sample size and statistical power must be improved. Furthermore, the relatively simple microFE models used in this study are based on strong assumptions of material homogeneity, isotropy and linear elasticity. We are current developing models to account for accurate recovery of the smooth boundary by using tetrahedral mesh and by improving the assignment of the material properties to account for local heterogeneities and nonlinearities.

To conclude, this study showed that the combination of *in situ* mechanical testing, microCT imaging and DVC algorithm can be used to validate microFE models of bone samples at different dimensional levels.

Acknowledgments

This study was partially funded by the EPSRC (MultiSim Grant No. EP/K03877X/1), the FP7 European program (PIEF-GA-2012-327357), and the Sheffield Hospital Charity (141515-1). The authors thank Dr Danesi and Mr Palanca for the help with the sample preparation, testing and scanning. Prof Barber and Prof Hose are also acknowledged for sharing the ShIRT algorithm.

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