University of Technology, Sydney

Faculty of Science

Analysis of trabecular bone mechanical properties from magnetic resonance images

Thesis submitted for the degree of

PhD in Science

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CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Student

ACKNOWLEDGMENT

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Dedication

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List of Abbreviations

aBMD	Areal bone mineral density
BMD	Bone mineral density
BV/TV	Bone volume fraction
CT	Computed tomography
DICOM	Digital Imaging and Communications in Medicine
DXA	Dual energy x-ray absorptiometry
FE	Finite element
FEA	Finite element analysis
FEM	Finite element method
FID	Free induction decay
FLASE	Fast large-angle spin echo
FLASH	Fast low-angle shot
FSE	Fast spin echo
HR-pQCT	High resolution peripheral quantitative computed tomography
IDL	Interactive Data Language
IGFA	Image guided failure assessment
IOF	International Osteoporosis Foundation
MIMICS	Materialises Interactive Medical Image Control System
MR	Magnetic resonance
MRI	Magnetic resonance imaging
MSE	Multiple spin echoes
MTD	Main trabecular direction
NMR	Nuclear magnetic resonance
PCG	Preconditioned conjugate gradient
PBS	Phosphate buffered saline
PD	Proton density
PVE	Partial volume effect
QCT	Quantitative computed tomography
RF	Radio frequency

SE	Spin echo
SNR	Signal-to-noise ratio
Tb.N	Trabecular number
Tb.Sp	Trabecular separation
Tb.Th	Trabecular thickness
TE	Echo time
TR	Repetition time
µCT	Micro computed tomography
µMRI	Micro magnetic resonance imaging
vBMD	Volumetric bone mineral density
WHO	World Health Organization

ABSTRACT

Bone mineral density (BMD) measured by dual energy x-ray absorptiometry (DXA) is often used in the clinical diagnosis of bone disorders such as osteoporosis. However, several studies have shown that measuring BMD alone does not provide sufficient discrimination between individuals with and without increased fracture risk. In fact, bone quality is affected also by the bone micro-architecture and material properties. The development of imaging techniques, particularly computed tomography (CT) and magnetic resonance (MR) imaging, allowed the generation of three-dimensional (3D) images for the morphological analysis of trabecular bone. Furthermore, the 3D image data can be the source of finite element (FE) models. FE analysis of such data represents a means to assess the mechanical response virtually. Whole-body CT and MRI scanners are able to provide three-dimensional images *in vivo* of human femoral and spinal sites but compared to µCT and µMR, have poorer resolution and lower signal-to-noise ratio. As a result of the low resolution, a significant partial volume effect is expected to affect the reconstructed images primarily by blurring the interface between bone and soft tissue. Thus, the implications of such limitations on the FE assessment of mechanical properties should be investigated.

The main goal of this study was to assess the capability of whole-body low resolution MRI-based finite element model for the prediction of trabecular bone mechanical properties. The apparent elastic modulus and the displacement field were assessed and compared to a high resolution MR model. The effect of image voxel

size on these properties was examined using µMR images acquired with different resolutions.

The estimated mechanical properties of two trabecular bone samples (A and B), as assessed by whole-body MRI-based FE analysis, were compared with the corresponding measurements obtained from the validated µMRI-based FE analysis. It was found that increasing the voxel size from 30 µm to 200 µm raised the apparent elastic modulus by up to 13% and 21% for bone samples A and B, respectively. For whole-body MR, with voxel size of 260 µm, the overestimate rose to 24% for both bone samples. However, the apparent tissue elastic modulus stayed within the range (722- 1207) MPa, and (777 – 1228) MPa for bone samples A and B, respectively, imaged with high resolution µMR. The variations in the apparent elastic modulus appear to correlate with differences in the bone volume fraction, which varied between 0.44 and 0.68. FE analysis of load levels in the elastic range indicated that the more computationally costly geometric non-linear analysis did not improve the results significantly. Hence, a linear elastic FE analysis was deemed to be sufficiently accurate at low load levels.

In addition to estimating the apparent elastic modulus, FE analysis can produce a displacement field that represents the response to applied compression at every point in the trabecular bone. The results show that increasing the voxel size leads to a systematic overestimation of the mean displacement compared to the reference values. However, the mean norm displacement estimated from whole-body MR (0.64 mm) in the direction of the applied compression force falls within the range obtained from high resolution µMR (0.64 ± 0.13 mm). The results also suggest that the information provided by displacement field values may be statistically uncorrelated with the apparent elastic modulus and hence serve as an additional source of parameterization of the mechanical response of trabecular bone.

The application of whole-body MRI to trabecular bone analysis is expected to be affected not only by resolution but also by other effects arising from the low strength of the steady magnetic field, the large imaging volume, and motion artefacts. Nevertheless, both the estimated apparent elastic modulus and displacement field are compatible with those obtained from μMR of comparable resolution.

Within the limit of this study the predictions of FE analysis derived from whole-body MR are within the range of predictions based on high resolution μMR, indicating a potential suitability of MR for assessment of bone strength.