Micro-Computed Tomography
Studies of Biomaterials and Bone

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Except where otherwise indicated, this thesis is my own original work.

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Abstract

This thesis is presented in two parts; the first part is a study of the structure and properties of bioceramic scaffolds used for orthopaedic tissue engineering and how these factors may influence bone regeneration. The second part of this thesis is a study of the effects of bone microarchitecture on the mechanical properties of the human proximal femur.

Strategies for orthopaedic tissue engineering involve the use of a porous ceramic or polymer scaffold to serve as a template for bone regeneration. However, the design and engineering of these scaffolds is ad hoc. The effect of porosity, pore size, shape, interconnectivity, transport and mechanical properties on bone ingrowth is not well understood and remains a significant challenge to successful bone regeneration.

We use a 3D micro-CT imaging and analysis approach to generate measures of local and non local pore size, pore interconnectivity, transport and mechanical properties directly from images of explanted hydroxyapatite constructs from a sheep model.

We develop a method to accurately phase separate pore, bone and scaffold phases using a three-phase segmentation algorithm. We also observe a strong correlation with bone ingrowth and measures of non local pore size which account for pore accessibility. This study demonstrates the utility of micro-CT and quantitative 3D analysis to analyse tissue engineered implants.

Osteoporosis and bone fracture at the hip are increasingly common with an aging population. Current methods to diagnose and treat osteoporosis are ambiguous about the role of bone microstructure in bone fragility.

A micro-CT and 3D imaging approach on 13 proximal femora is implemented. We derive corrections to the standard Hip Structural Analysis assumptions of square and circular cross section at the femoral neck. A finite element method (FEM) is used to estimate the full anisotropic elastic stiffness tensor and correlations are noted with age, and structural parameters (such as topology and porosity). The strength of hips has been inferred via modulus-porosity relationships undertaken on trabeculae from within the femoral head and neck. We show that the modulus-porosity relationships at the whole hip scale differ significantly (by 100-200%) from relationships derived on trabecular subsets. Therefore, empirical relationships of modulus-porosity for trabeculae do not match data at the whole hip scale; a different empirical scaling and better fit is derived. Decreases in Young’s and shear moduli were observed with age while
increases of moduli were noted with mean coordination number. We also note a resolution dependency with estimation of elastic properties and recommend a voxel size less than 25\(\mu\text{m}\) for quantitative mechanical studies.
Glossary

Anisotropic diffusion
An edge-preserving smoothing filter for tomographic images. 17

Autologous
An implant into a patient in which the graft tissue is derived from the same individual. 1, 10

Bioactive
A material that interacts with surrounding tissue when implanted, e.g. synthetic hydroxyapatite, and Bioglass. 1, 57

Biocompatible
The capacity to be well tolerated by the body without any adverse reactions. 2

Bioinert
A material that does not react or release any ions upon contact with biological tissues. 1

Bioresorbable
A material exhibiting breakdown and dissolution within the body. 11

BMC
Bone mineral content. Measured from x-ray absorbance on a DEXA scan. 70

Capillary radius
A measure of pore size based upon the equivalent pore radius of an invading non-wetting fluid into the pore space. Also called the accessible pore radius. 20, 49

Coarse graining
Replacing a high resolution image with a lower resolution image by averaging or smoothing. 140

Conjugate gradient
A numerical technique for the solution of linear systems. 44, 108
Glossary

Coordination number
The number of neighbours connected to a particular node of a network. 22, 43, 104

DEXA
dual energy x-ray absorptiometry. 69, 70, 78, 83, 87

Endocortical
Relating to the surface between the cortex and the medullary. 66

FDM
Fused deposition modelling. 12, 38

FEM
Finite element method. 44, 92

FH
Femoral head. 88

Fiducial
An envelope that encloses the object of interest. 19, 103

FN
Femoral neck. 63

FNAL
Femoral neck axis length. Measured from the most lateral point on the greater trochanter to the most medial point on the femoral head. 69

HAp
Hydroxyapatite. 12

Histology
The study of microscopic structure of biological tissues. 11

HSA
Hip structural analysis. A standard technique for extracting strength-related parameters from 2D x-ray images of the hip. 63

Interconnectivity
A property of a network that describes the degree to which different nodes are connected together. 10, 19, 37
Glossary

Intertrochanteric line
A line that separates the femoral neck from the shaft of the femur. 72

Intracortical
Relating to the region within the cortex. 66

Kernel
A matrix of values used to filter an image. 19, 103

MCS
Maximum covering sphere. A measure of pore / solid size. At each point a size is defined as the radius of the largest sphere containing that point and which is also completely contained within that phase. 19, 35, 40

Medial axis
An axis that approximates the centre of an object. 40, 104

Medullary
The region within the bone occupied by the marrow. 75

Mesoscopic
The scale above which the fluctuations of individual particles or atoms do not dominate the observation of an averaged property or phenomena. 45

Monoenergetic
Radiation consisting of photons whose energies are within a very narrow range. 6

Morphological closing
An image processing algorithm to remove small holes; dilation followed by an erosion. 19, 103

Morphological opening
An image processing algorithm to remove small objects; erosion followed by dilation. 73

Morphology
The study of form and structure. 11, 21, 84, 118, 121

NSA
Neck shaft angle. The angle formed by a line drawn through the shaft of the femur with one passing through the axis of the femoral neck. 69
Padding voxels
A layer of voxels surrounding an image. 44

POF
Pore occupancy fraction. The ratio of bone volume to pore volume for a given volume or pore. 21

Region merging
An algorithm to combine labels or clusters in an image according to their relative shape, size and separation. 40

Section modulus
A measure of a beam’s resistance to bending. Calculated as the ratio of the cross section’s second moment of area to its greatest distance from the neutral axis. 73

Segmentation
An algorithm for partitioning digital images into multiple regions. 14, 99

Trilinear element
A cubic finite element with eight nodes - one at each vertex. Quantities of interest can be interpolated linearly from the eight nodes. 44

UNSW
University of New South Wales. 12

vBMD
Volumetric bone mineral density. Calculated as the bone mineral content (BMC) divided by bone volume. 68

Voxel
A 3D volume element. 6

Watershed
An image processing algorithm for partitioning an image into multiple regions. 40
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