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Permeability study of cancellous bone and its idealised structures

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ABSTRACT

Artificial bone is a suitable alternative to autografts and allografts, however their use is still limited. Though there were numerous reports on their structural properties, permeability studies of artificial bones were comparably scarce. This study focused on the development of idealised, structured models of artificial cancellous bone and compared their permeability values with bone surface area and porosity. Cancellous bones from fresh bovine femur were extracted and cleaned following an established protocol. The samples were scanned using micro-computed tomography (μCT) and three-dimensional models of the cancellous bones were reconstructed for morphology study. Seven idealised and structured cancellous bone models were then developed and fabricated via rapid prototyping technique. A test-rig was developed and permeability tests were performed on the artificial and real cancellous bones. The results showed a linear correlation between the permeability and the porosity as well as the bone surface area. The plate-like idealised structure showed a similar value of permeability to the real cancellous bones.

1. Introduction

Ageing or skeletal diseases such as osteoporosis and osteoarthritis have direct influence on the mechanical properties of cortical and cancellous bone [1–4]. The human metabolic system and the physiological activities affect the supply of nutrients to these bones [5,6] and therefore influence the growth of mass, architecture and tissue properties. With reduced physiological activity, the nutrients supply will deteriorate, affecting the ability of cancellous bone to self-repair or remodel [7]. The mechanobiological movement of nutrients through the porous cancellous bone plays an important role in ensuring bone quality and affect the evolution of bone pathology [6–8].

Autografts and allografts have been widely used for bone repair. However, these methods have several limitations such as donor site morbidity, pain, infection, limited donor bone supply, anatomical variation [8–12]. Due to these limitations, artificial cancellous bones can be used as an alternative to autograft and allograft. However, developing a synthetic cancellous structure that mimics the real cancellous bone architecture is highly very challenging due to their heterogeneous and anisotropic properties [13–16], as well as the vast microarchitectural variations between skeletal sites [8,17–19].

Due to the complexities of the structure, the development process of the synthetic structure must be done thoroughly to achieve characteristics close to the natural cancellous bone. The main factors that should be taken into account in the design and development of synthetic cancellous structures are the transport phenomena, or permeability, as well as the mechanical properties. Whilst there are numerous literatures reporting the mechanical properties of cancellous structure [2,10–13,15,20–30], the transport phenomena received little attention [5,31–35]. The permeability of the cancellous bone structure, which indicates the ability to transmit nutrients through the porous media, is an essential parameter for quantifying the mechanical behaviour of the interstitial fluid [36]. Mechanical loading generated from physiological activities deforms the cancellous structure causing fluid flow through the porous media. The porosity [5,8,31–33] and bone surface area, as has been reported by several researchers, affect the hydraulic permeability of the cancellous bone structure. The porosity of cancellous bone has two main purposes i.e. to reduce the overall weight whilst maintaining the required strength locally [33,37,38], and to allow nutrients to pass through [5,35].

This paper focused on the permeability of natural and synthetic cancellous bone structures. For the construction of synthetic idealised bone models, microarchitecture of cancellous bones was

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categorised into a combination of rods and plates [3,11,39,40] with varying pore sizes [33,41,42]. The porosity of cancellous bone is dependent on the anatomic site, morphological indices and direction of the struts. The indices that have been widely used in the correlation include the bone volume fraction (BV/TV), bone specific surface (BS/TV), trabecular thickness (Tb.Th), trabecular separation (Tb.Sp), trabecular number (Tb.N), mean intercept length (MIL) [21,43], density [21], rod-like, plate-like, and a combination of plates-and-rods [3,11,39,40].

Permeability studies of cancellous bone microarchitecture through experimental means have been carried out by numerous researchers [5,31–35] where relationships between permeability, morphology parameter and anatomical site were reported [6,32,33]. To the best of our knowledge, no experimental work has been undertaken to directly compare permeability between natural and synthetic cancellous bone structures using a pulsatile pump to simulate physiological activities. There are, however, some simulation studies conducted in 2D [44] and 3D analysing idealised porous scaffold [45], unit cells of foams [46] as well as in bulk form [47]. The work on general cellular materials included experiments on metals [48–50], ceramics [51,52], combination metal-ceramic foams [49], and sandstone [53]. The specific objective of this study is to develop three-dimensional models of synthetic cancellous bone and compare their permeabilities as well as their relationships with physical properties such as bone surface area and porosity. The outcome of the analysis will provide information in terms of the type of synthetic structure that can best represent the natural cancellous bone.

2. Methodology

2.1. Specimen preparation

A freshly harvested, bovine hind-limb was bought from a local slaughterhouse. Twenty-five uniform bone cylindrical core specimens (10 mm in diameter and 15 mm in length) were extracted from three different anatomical sites. The specimens were taken from the mediolateral femoral condyles ($n = 5$), neck of femur ($n = 9$) and greater trochanter ($n = 11$).

The neck of femur was excised from the region of whole femur by making two mutually perpendicular cuts along the long axis of the femoral neck. The femoral head and greater trochanter have been cut parallel to the pelvic orientation and perpendicular to the axis of the femur neck shown in Fig. 1a. Furthermore, the cylinder specimen was taken from the major trochanter of the femur; its cores were cut perpendicularly along the aligned axis of the femur. It means that the cylindrical specimen aligned with the principal trabecular orientation was cored [5,54]. These cutting processes consisted of two main parts of major and minor trochanter as shown in Fig. 1b. The cores cylinder specimen was drilled in the drilling orientation as shown in Fig. 1. The mediolateral femoral condyles specimen was drilled oriented in inferior–superior (longitudinal) direction of the specimen [5,33] as shown in Fig. 1c. Before that, the femur cadavers were cut into rectangular by cutting parallel to the medialepicondyle and lateralepicondyle. Onwards, the cutting process was also done at the medial and lateral condyle section due to the end of intercondylar fossa. In another section on the end of the distal tip line of capsular reflection were also cut parallel to the cutting line of meidal and lateral condyle.

A slow speed diamond saw under constant lubrication was used to minimise heat generation and unnecessary breaking of struts at the edge. Saline water was used as lubricant to ensure that the temperature did not exceed 46 °C, and therefore, protecting the specimens from heat-related damage [55]. The hard cortex was removed and cancellous samples were drilled into cylindrical forms with a total length of 15 mm and a diameter of 10 mm. A 1.5 mm thick diamond-tip coring bit was used at a slow speed of 150–250 rpm [12] to drill the cancellous bones. The slow speed of the diamond-tip cut produced a smooth surface and minimised struts breakage.

The cylindrical bone samples were then cleaned using an ultrasonic cleaner [12,34] with a chemical detergent for 3 h [5,33]. Water jets and air jets were used to remove any excess of water, fat and bone marrow from the bone samples. The procedure was repeated until no bone marrow could be detected upon visual inspection [5,32]. The bone samples were then dried using an air jet and stored in a freezer individually in an airtight plastic bag to minimise thermal cycling [21,56–58]. The temperature of the freezer was set to −20 °C [21,33,56–58].

An electronic calliper was used to measure the length and diameter of the specimens based on the mean of ten random measurements using the coefficient of variation, in the range of below 5%. The volume of the core cylinders was calculated as:

$$V_{\text{Cylinder}} = \frac{\pi d^2}{4} L \tag{1}$$

where L is the specimen length and d is the specimen diameter. The mass of the cancellous bone sample was cleaned from marrow, fat and water content, recorded and the apparent density of the bone sample was calculated using Eq. (2):

$$\rho_{\text{apparent}} = \frac{\text{Mass of cancellous bone sample}}{\text{Volume of cancellous bone sample}} \tag{2}$$

Determination of porosity and volume fraction of the cancellous bone sample was done using Archimedes' method [5,32,33,59]. The cancellous bone samples were cleaned and stored in a freezer at a temperature of −20 °C and degassed under vacuum. After vacuumed and submerged, the weight of each cancellous bone samples was measured using a digital scale (Precisa-XB). The volume of cancellous bone core can be determined as follows:

$$\begin{aligned} &\text{Mass of cancellous bone sample} \\ &\quad - \text{Apparent mass when submerged} = \text{Density of water} \\ &\quad \times \text{Volume of cancellous bone sample} \end{aligned} \tag{3}$$

The porosity (ε), was also calculated by [32,46,52]:

$$\varepsilon = \frac{V_0 - V}{V_0} \tag{4}$$

where V_0 is the total volume of a cancellous bone sample and V is the volume of the cancellous bone sample that the bone struts occupy.

Bone surface area was measured via computational means. The bone specimens were scanned via μCT (Skyscan 1172, Kontich, Belgium) at an approximate spatial resolution of 17.20 μm. The raw dataset in dicom format comprised of 2D images of trabecular structure in cylindrical form with a slice thickness of 0.1 mm. The datasets were then used to construct three-dimensional model of the specimens using Mimics software (Materialise, Leuven, Belgium). The completed models were then converted to finite element meshes and exported to MARC.Mentat software (MSC Software Corp., California, USA). The value of bone surface area was obtained via this software.

2.2. Design and fabrication of 3D model synthetic cancellous bone

The synthetic cancellous bone models were developed and fabricated with several types of structures such as BCC, FCC, sintered spheres, tetrakaidecahedral plate like, tetrakaidecahedral rod like, prismatic plate-like and prismatic rod-like. A morphology study of