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Journal of Biomechanics 41 (2008) 438–446

JOURNAL OF BIOMECHANICS

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Dependence of mechanical compressive strength on local variations in microarchitecture in cancellous bone of proximal human femur

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Accepted 10 August 2007

Abstract

Human cancellous bone is a heterogeneous material. Despite this, most of the published studies report correlations between mechanical properties and morphometric parameters averaged on the whole specimen.

This work investigated whether local variations in morphometric parameters were linked to the localized failure regions of cancellous bone. Additionally, it was examined whether local values of morphometric parameters can predict the ultimate stress better than the average bone volume fraction (BV/TV).

Cylindrical cancellous bone specimens extracted along the primary compressive group of human femoral heads were studied. These were microCT-imaged to assess the morphometric parameters, compressed to determine the ultimate stress, and rescanned by microCT to visualize the failure region.

Failure involved slightly less than half of the free height of the specimens. Significant differences were found in the morphometric parameters calculated in the failure and in the non-failure regions. The cross-sections containing minimum BV/TV values were those most often located inside the failure region (83%, $p<0.001$). Regression analysis confirmed that variations in BV/TV best describe variations in ultimate stress ($R^2 = 0.84$) out of the averaged morphometric parameters. The prediction of ultimate stress increased when minimum or maximum values of the morphometric parameters were taken, with the highest prediction found by considering the minimum BV/TV ($R^2 = 0.95$).

In conclusion, due to the heterogeneity of cancellous bone, there may exist regions characterized by a different microarchitecture, where the bone is weaker and consequently is more likely to fail. These regions mostly contain minimum values in BV/TV, which were found to predict ultimate stress better than average BV/TV.

Keywords: Cancellous bone; Trabecular architecture; Morphometric parameters; Mechanical testing; Bone strength

1. Introduction

Bone fractures represent a major health problem in the increasingly elder population. The World Health Organization (WHO) recommends the use of bone mineral density (BMD) measurements to determine fracture risk (WHO, 1994). However, while BMD is correlated to fracture risks, using it to identify individuals who will suffer a fracture is not always reliable (Marshall et al., 1996; McCreadie and Goldstein, 2000). Furthermore, BMD measurements alone neither allow to differentiate between cortical and cancellous bone, nor to determine structural changes within the cancellous bone microarchitecture.

Apart from density, cancellous bone microarchitecture has an important effect on bone strength (McCalden et al., 1997; Gibson, 2005). Spatial resolution is one of the key-parameters for the morphometric quantification of cancellous bone microarchitecture (Müller et al., 1996b). The development of high resolution 3D imaging techniques, such as microtomography (microCT) or high resolution magnetic resonance imaging, has made it possible to assess cancellous bone structure in three dimensions non destructively (Müller et al., 1996a; Majumdar, 1998). A number of studies have found significant correlations between mechanical properties and morphometric parameters (Goulet

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0021-9290/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2007.08.003

et al., 1994; Majumdar et al., 1998; Ciarelli et al., 2000; Ding et al., 2002). Although cancellous bone is a heterogeneous material, in those studies the average values of the morphometric parameters were used. Wachter et al. (2001) hypothesized that inside the bone specimen there may be a structural plane, characterized by a different cancellous bone structure, acting as the weakest link at which fracture may initiate. However, in that study, which was done by using peripheral quantitative computer tomography (pQCT), no morphometric parameter was found that could explain the variations in ultimate stress better than BMD. In a recent study based on time-elapsed compression on cancellous bone samples extracted from a single whale vertebra, microCT animations showed that failure occurred in local bands with the remaining regions of the structure largely unaffected (Nazarian and Müller, 2004). This last report suggested that localized failures of cancellous bone correspond to local variations in cancellous bone structure. In a subsequent work, the same group found that in cancellous bone specimens extracted from human vertebrae, failure is mostly localized within the subregion showing a minimum value in bone volume fraction (BV/TV) (Nazarian et al., 2006). Furthermore, in the same study, it was found that the minimum value of BV/TV is a better predictor of mechanical failure in cancellous bone than BV/TV of the entire specimen. Those results were obtained on vertebrae retrieved from two subjects, at the lower limit of the density range for human cancellous bone ($BV/TV = 5.6 \pm 1.2\%$). It remains to investigate whether the similar findings may be found also in high density human bone specimens, such as those extracted from the femoral head (Hildebrand et al., 1999), of several subjects.

The aim of the present study is to investigate whether local variations in morphometric parameters are linked to the localized failure regions of cancellous bone extracted from the human femoral head of several subjects. Additionally, it is examined whether these local values of morphometric parameters, described by their minimum or maximum values, can predict the ultimate stress better than the average values of bone volume fraction. To minimize the variation in the measured mechanical properties due to the testing direction, the cancellous bone was compressed along the main axis of the trabeculae in the primary compressive group of the head (Ohman et al., 2007).

2. Materials and methods

2.1. Bone samples

Fifty human femoral heads were collected from different subjects (mean age 67 ± 13 years). Samples were obtained from dead persons without pathologies thanks to a donor program (International Institute for the Advance of Medicine, Jessup, PA, USA) or from patients undergoing total hip arthroplasty having different pathologies (primary coxarthrosis, osteoporosis, rheumatoid arthritis). A written informed consent was obtained from the patients.

Before machining, the samples were fixed in a 70% ethanol solution for at least four weeks to reduce the risk of disease transmission. This preservation method, with effects similar to freezing and thawing, changes slightly the viscoelastic properties (hysteresis energy and loss tangent), but does does not alter significantly the stiffness of cancellous bone (Linde and Sorensen, 1993).

2.2. Extraction of a cancellous bone cylinder

From each femoral head, a cylindrical specimen containing cancellous bone from the primary compressive region was retrieved, with the cylinder axis aligned with the superior–inferior main trabecular direction (MTD) (Fig. 1).

Prior to extraction, the MTD was identified in the femoral head as follows: steel spheres (1 mm diameter), which were used as landmarks, were attached on the femoral head surface on two lines lying on two orthogonal planes (Fig. 2). Then, two frontal X-ray images were taken by microCT (desktop microCT system, Skyscan model 1072, Skyscan, Aartselaar, Belgium) (Sasov, 1987; Sasov and Van Dyck, 1998) and used to identify the MTD. The microCT scanner works with cone-beam geometry, which gives frontal X-ray images as large as 20 mm × 20 mm within a few seconds. The rotation stage of the microCT system has a total vertical excursion of 25 mm. By taking X-ray images at the minimum, middle and maximum height of the rotation stage and then pasting them together, a total height of about 45 mm can be imaged. Since a typical femoral head is about 40–60 mm in diameter, operating this way a large part of the femoral head can be X-ray imaged, in order to identify the MTD for the extraction of the bone cylinder (Fig. 2). Then, about 5 mm of the proximal part of the head was cut in a plane orthogonal to the MTD, under constant water irrigation of the sample, using a diamond saw. A second cut was performed parallel to the first plane, obtaining a 26 mm thick bone slice (Fig. 3). The bone slice was positioned in a computer controlled milling machine. Using a holed diamond-coated milling cutter, with the slice immersed in water, a cylindrical bone specimen (height 26 mm, diameter 10 mm) was extracted, with the cylinder axis aligned with the MTD (Fig. 3).

2.3. MicroCT scanning

A polymethylmethacrylate (PMMA) endcap was applied onto one end of each of the 50 specimens, by submerging the specimen 3 mm of its

Fig. 1. Radiograph example of a proximal human femur, showing the main trabecular direction (MTD, dashed-dotted line) in the principal compressive region along which the specimen had to be extracted in the present study.