Directional Variation of Trabecular Bone in the Femoral Head, a μ-CT based Approach

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Abstract: The structural characteristics of bone are described by features of high complexity, defining the directional anisotropy of its mechanical properties. This phenomenon originates in the orientation of collagen fibers and osteons within the cortical tissue and the trabecular morphology of cancellous bone. the purpose of this study was the examination of the geometrical anisotropy of cancellous bone in the femoral head. 28 femoral heads, harvested during hip replacement of 17 women and 11 men, were studied in total. Cylindrical specimens of 11mm in diameter were extracted perpendicular to the fovea capitis femoris and subjected to micro Computed Tomography (μ-CT). a 11mm sphere was isolated from all samples and the cross-sectional area of the sphere was studied for 8 predefined regions, corresponding to planes perpendicular to principal loading directions of the hip joint. Significant topographical variations of trabecular bone structure in different subchondral regions were determined. in the superior region, the trabecular bone strength was the highest, while the inferior region exhibited the lowest bone strength and medial and lateral regions had intermittent magnitudes. No significant difference in anisotropy was found between male and female samples, although the absolute values were greater in males. The obtained results cohere with recent literature data of osteopenetration experiments in these directions.

1 INTRODUCTION

Trabecular bone is a major load bearing tissue of our musculoskeletal system. When modelling anatomical sites with large bones (Khosla et al., 2006) or structures consisting of both, cancellous and cortical bone (Tsouknidas et al., 2012a) the simulation is less sensitive on micro-architectural variations due to the thicker cortices. When assessing however, therapeutic efficiency, implant stability or fragility fractures, cancellous bone remains a major qualitative determinant.

The proximal femur is an anatomical site of major interest to clinicians as its mechanical failure is one of the most common reasons for pain and morbidity (Rockwood et al., 1990); (Cooper et al., 1992). The primary bearing surface in the hip joint is the articular cartilage. The subchondral cancellous bone is located deep inside the articular cartilage and the percentage of the load carried by this tissue varies from 4% at the base of the neck to as much as 70% in the subcapital region (Lotz et al., 1995). This suggests that cancellous bone plays an important role in the mechanical strength of the proximal femur and especially of the femoral head. Cancellous bone however is not homogenous, it is characterized by a microstructural anisotropy, that drastically affects its biomechanical response to loading. There exists a consensus in literature, that trabecular bone is organized and oriented, in order to adapt to the mechanical loads it is subjected to, this process is based on continuous bone resorption followed by bone formation during remodeling (Raisz, 2005).

The purpose of this study was to examine the micro architectural anisotropy of cancellous bone in the femoral head and detect possible variations based on the patients' Bone Mineral Density (BMD).

2 MATERIALS AND METHODS

Twenty-eight femoral heads from 17 female and 11 male patients, undergoing total hip arthroplasty, were studied. The mean age of the patients was 75.6

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years (range, 63 – 88 years). The specimens were harvested during operation (Tsouknidas et al., 2012b) and frozen/stored at -60^o C, upon receiving written consent from all patients. None of the patients had been diagnosed with any type of metabolic disease or cancer and no bone cysts were apparent in any of the femoral heads. All cases with evidence of osteoarthritis, rheumatoid arthritis, avascular necrosis, osteomalacia or secondary osteoporosis due to corticosteroids were excluded from the study. Cylindrical specimens were extracted perpendicular to the medial region, by means of a hole saw.

Prior to extraction, the patients' Bone Mineral Density (BMD) was measured through Dual-energy X-ray absorptiometry (DXA) and recorded for further use. a major strength of this study is reflected by the wide range of BMD considered, varying in both gender and patient condition (from healthy to osteoporotic). This is due to the fact that trabecular bone is a highly porous tissue differing substantially not only across individuals but also between anatomical sites and thus varying BMDs can be used for studying many applications (Tsouknidas et al., 2011).

All harvested specimens were immersed in a 200 kHz ultrasonic bath with a 1% enzyme solution by Alconox to assimilate the proteinaceous tissue and repeatedly cleaned until completely defatted (Nauman et al., 1999). Upon drying, the specimen was weighted with a micro-scale of a 100μg resolution (Mettler Toledo) and their apparent density (ρ_{ap}) calculated using equation (1).

$$\rho_{ap} = \frac{m_d}{\pi d^2 h} \quad (1)$$

where m_d represents the weight of the dry specimen d and h its diameter and height respectively. This resulted in an apparent density of the specimens ranging from 2.19 to 3.35 g/cm^3, as presented in table 1.

The specimen was scanned with a μ-CT device (Werth TomoScope® HV Compact) to reconstruct its 3D shape. The measurements were conducted at a spatial resolution of 10μm, a high image resolution was chosen as there exists a consensus throughout literature that measurement accuracy directly affects geometric discretization and model convergence (Bevill and Keaveney, 2009). Data acquisition was in accordance to DICOM (Digital Imaging and Communications in Medicine) this allowed the conversion of multiple 2D images into a 3D volume. Interpolation of the obtained measurements ensured higher representation accuracy, even though this process did not result in higher resolution of the sample. the smoother representation facilitated the distinct removal of the remaining soft tissue, which was either not visible or accessible during the initial defatting process. a semi-automated segmentation technique, supported by manual correction of the threshold results was followed. during this multi threshold segmentation, the mean grey-scale within the image is calculated and sensitive edge detection filters are employed (Rathnayaka et al., 2010); (Canny, 1986), to distinguish the apparent tissue types. The reconstructed sample consisted of porosity ranging from 68.52 to 91.38%. All the determined characteristics of the sample are in agreement with data found in literature (Baroud et al., 2004).

Table 1: Volumetric data obtained from the measurements, reported as mean ± standard deviation.

Gender	BMD	ρ_{ap} [g/cm^3]	BV/TV
Male	0.62±0.07	3.23±0.62	0.24±0.05
Female	0.49±0.11	2.47±0.89	0.21±0.06

The length of the specimens was approximately 25mm and upon scanning, a sphere within the cylinder was isolated, as illustrated in figure 1. the position of the sphere was carefully selected in order to represent the centre of the femoral head for each of the samples. This allowed direct comparison of the samples in terms of cross-sectional bone area.

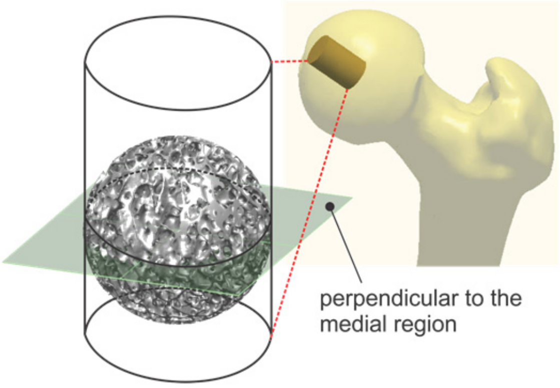

Figure 1: Extraction direction of the harvested specimens.

In our study eight different orientations, representing directions perpendicular to a specific region of the femoral head were examined, as demonstrated in figure 2. the medial region (reg-1) which is located in fovea capitis femoris, the inferior region (reg-2), the medial-superior region (reg-3), the superior region (reg-4), the anterior region (reg-5), the anterior-medial region (reg-6), the posterior-medial region (reg-7) and the posterior region (reg-

8). The 8 different sites represent regions subjected to different amounts of loading in vivo (Thomas and Daniel, 1983); (Hodge et al., 1986).

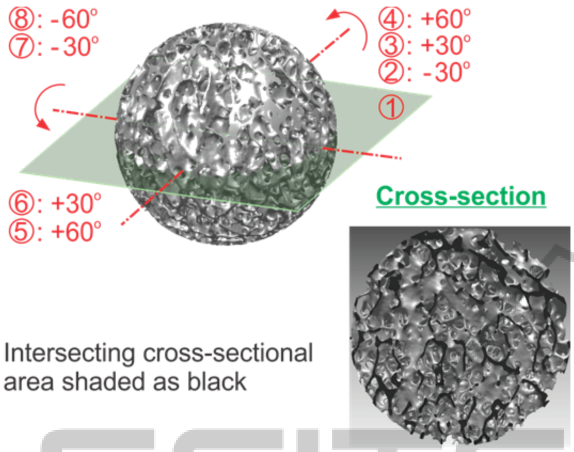

Figure 2: Trabecular sphere and cross-sectional area.

3 RESULTS

There were significant topographical variations of trabecular bone strength in different subchondral bone regions.

In the medial region (1) and the inferior region (2) the mean cross-sectional area was the lowest, wherease the highest were registered in the superior (4) and medial-superior region (3). The anterior region (5), anterior-medial (6) and posterior-medial region (7) exhibited average values, which were slightly enhanced in the posterior region (8). The results are symmetrized for both male and female donors in figure 3.

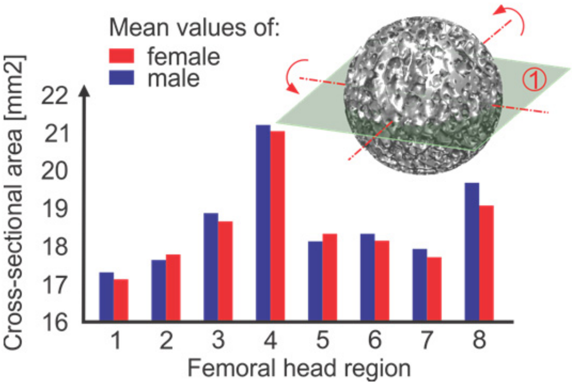

Figure 3: Mean cross-sectional areas registered for the 8 primary subchondral regions.

According to these results, the 2D trabecular bone density in the superior and medial-superior regions is higher and thus bone strength is predicted to be elevated in this region which is expected to compare favourably to the fovea capitis femoris. The bone density is lower in the orientation of the fovea capitis femoris which should prove more susceptible to compression, whereas anterior and posterior regions reflect similar cross-sectional areas.

No significant difference in anisotropy was found between male and female samples, although the absolute values were greater in males.

4 DISCUSSION

In this study eight different regions of the femoral head were examined. The eight sites represent regions subjected to different amounts of in vivo loading. The superior region being the most heavily loaded, posterior and anterior partially loaded and medial and inferior being the least loaded. Our findings are in agreement with loading distribution described in other studies (Thomas and Daniel, 1983); (Hodge et al., 1986) and converge exceptionally with a recent study (Tsouknidas et al., 2012c), investigating the energy required for osteopenetration in the aforementioned sites, as indicated in figure 4. The figure represents the mean values of penetration energy required throughout the tested specimens.

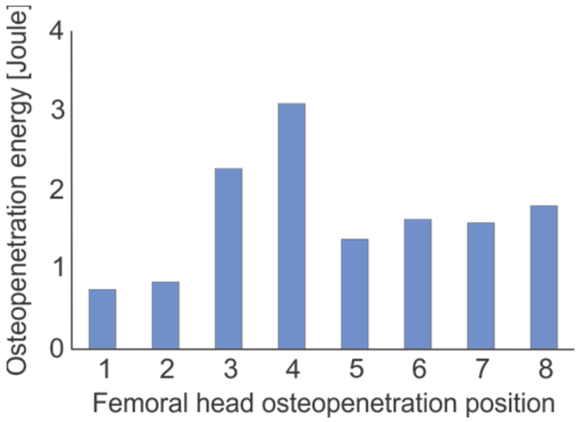

Figure 4: The mean values of penetration energy in the 8 regions.

The motivation behind our study is to correlate the attained values to architectural metrics which can be measured through 3D distance transformation techniques (Bevill and Keaveney, 2009). These characteristics can be easily obtained through porosity analysis modules, integrated in the visualisation software of contemporary CT devises, providing physicians with a valuable and non-invasive assessment tool for bone quality and strength.

An independent verification of our results is of course required and foreseen. in this context micro finite element simulations will be setup, to correlate our image analysis to compressive strength of the specimens. a verification of these models will be based on uniaxial compressive experiments of the harvested samples, conducted only in the primary direction (1), due to the destructive nature of the tests.

Brown et al. (1980) and Martens et al. (1983) performed compression tests by loading in three directions: anterior-posterior, superior-inferior and medial-lateral. They shown that anisotropy was evident and increase in stiffness was found in the regions traversed by the primary trabecular system (Brown et al., 1980); (Martens et al., 1983). However, in their studies bone specimens were obtained from nonspecific regions of the entire femoral heads. in our study we examined eight different but well defined orientations with similar positioning within the femoral structure. Sugita et al. (1999) examined the differences in anisotropy in osteoporotic bone in the primary compressive group of the femoral head. They found increased values of compressive stiffness in the parallel loading group compared with the perpendicular loading group, but the anisotropic behaviour of cancellous bone is reduced, and the femoral head became isotropic as the bone density decreased (e.g. in osteoporosis). The anisotropy of vertebral bodies was also examined in the literature. Mosekilde and Viidik (1985), found that bone strength was greater in the vertical than in the transverse direction.

Conclusively, we examined geometrical anisotropy of trabecular bone and found this to represent an important characteristic of this severely inhomogeneous structure. the conversion of our results with previous experimental findings, strengthens our hypothesis that micro scale imaging of the femoral head, at limited spatial resolution, may be used as an indicator of both, bone strength and anisotropy.

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