The Changing Microarchitecture of Trabecular Bone During Compression

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Introduction: Trabecular bone is a load bearing, distributing and shock absorbing material found at the ends of long bones, vertebrae and flat bones. Its complex micro-architecture and biphasic individual constituents hugely affect the macro mechanical behaviour of the bone which is largely unknown. Aging and bone disease can alter the micro-structure of the bone, which, in turn puts the bone at fracture risk. Although trabecular bone yields at small strains, large deformation analysis is necessary to understand the failure mechanisms and post-elastic nonlinear behaviour which facilitate the improved orthopaedic implant designs.

Our long term objective was to relate the change in micro-architecture to the continuum mechanical behaviour. In the current study we performed large compressive tests on trabecular bone samples from human femoral heads and assessed the microstructural indices. The specific aim of this study was to determine if there are any changes in the alignment or structure of the trabeculae during loading. Changes in the morphometry will elucidate how strain is distributed through the structure.

Methods: Human Femoral heads were harvested under ethical approval (2002/1/22) for the use of discard material in medical research. A core drill bit with a 10.64mm internal diameter was used to machine samples. The femoral head was securely held in a submerged clamp to negate heat production during machining. To prepare the samples for compression testing, the ends of the core samples were cut parallel using a Buehler Isomet low speed saw (Buehler, Illinois, USA) to a mean size of 12.15 (±0.65) mm.

6 samples were harvested and prepared from one osteoarthritic femoral head (Male, age 68). After preparation, the samples were inserted into a compression stage mounted in a Skyscan 1172 microCT (SkyScan, Kontich, Belgium) and scanned at a preload of 5N to obtain pre-loading reference properties. Load was applied at a rate of 0.01mm/s. In 3 cases, scans were conducted pre and post loading only (2 anterior, 1 posterior). In the remaining samples (2 central and 1 posterior) the samples were held and scanned at displacements equivalent to 2%, 4%, 6%, 8% and 10% strain. After full unloading, another scan was taken for all samples.

Scanning parameters of 17.22µm voxel resolution, voltage of 54 kV, Current at 185 µA and an exposure time of 0.885ms were used for all the samples. A 0.5mm Aluminium filter was located between the x-ray source and the sample. In order to ensure the bone had relaxed before scanning a wait period of 1000 seconds was implemented before starting each scan.

The images were reconstructed using NREC (SkyScan, Kontich, Belgium) to facilitate morphometric analysis using CTan (SkyScan, Kontich, Belgium). Reconstruction parameters were kept constant for all samples and a region of interest of 570 pixels (equivalent to a 9.8 mm circular shape) was used. Percent bone volume (BV/TV, %), Structural model index (SMI), Trabecular Thickness (Tb.Th, mm), Trabecular Number (Tb.N), Trabecular separation (Tb.Sp, mm) and Anisotropy (DM), and were derived.
Results: There is a large amount of variance in the distribution of bone throughout the femoral head. In order to evaluate the change in the microstructural indexes of each sample during compression (up to 10% strain) the data was normalised with respect to values corresponding to preload. The results from three samples from one osteoarthritic head are presented in figure 2. The data was analysed for statistical significance using an ANOVA (tukey). This analysis highlighted the following statistically significant differences (SSD) with a p value < 0.05.

BV/TV at 2% & 4% strain were SSD to 10%.

SMI revealed SSD’s between the post-load and 4%-10% strain, pre load and 2% strain were SSD to 10% strain.

Trabecular thickness (Tb.Th) showed SSD’s between the post-load and the preload - 6% strain, preload - 4% were also SSD to 8%, 10% and post-load.

The trabecular number (Tb.N) showed SSD’s between 10% strain and preload up to 6%, SSD’s were also seen between preload up to 4% and 8%, 10% and post-load.

Trabecular Separation (Tb.Sp) and Anisotropy did not show any significant differences during loading.

On all 6 samples, a paired t-test compared the values (not normalised) pre and post compression. SSD in BV/TV (p = 0.049) was found, implying that the bone does not return to the pre deformation structure. No other property displayed a SSD when comparing preload with post-load.

Discussion: During compression, the trabecular separation (Tb.Sp) and thickness (Tb.Th) are shown to decrease (Figure 3 c) and d)) which indicates that the pore space is reducing and the trabeculae are coming together. This was a continual process as the strain increased, however no significant difference was observed in the separation.

As the bone was loaded, the alignment of trabeculae was randomly changing with respect to its original state, resulting in a change in the degree of anisotropy. The qualitative movement of trabeculae (strain filed) between unloaded and compressed to 10% strain along longitudinal axis of one of the samples is shown in Figure 1d. The central core, extracted with the principal direction orientated along the femoral axis, had greater trabecular alignment than cores extracted from other locations. The trabeculae along this femoral axis were observed to be denser, more aligned and approaching to a more plat-like structure than other anatomical locations in the rest of the head. As we move away from the femoral axis towards the periphery the BVTV differs up to 3 fold. Furthermore, the alignment of the trabecular becomes increasingly random, which is represented by the parameter DA and BV/TV in Figure 2.

The SMI was found decrease as the bone was compressed. However, this does not mean that the trabecular bone is becoming a plate-like structure, rather the trabeculae are coming closer together as was registered in the images.

Significance: Frequently, implants under load in the body are considered for finite element analysis. The morphometry/bone architecture for this analysis is assessed in unloaded situations. Our data indicates significant changes in architecture under load. If trabeculae are modelled as a continuum (as in most large scale models) the changing architecture would result in different properties under load than would be derived from the unloaded scan data. This may affect how the load around an implant is distributed. This problem is magnified when we look at the bone architecture peripheral to the principal loading axis of the femoral head.
The change in micro-architecture at higher strains contributes to the change in nonlinear mechanical behaviour in post-elastic region. This is an attempt to relate the change in architecture to the mechanical behaviour of bone.
a) Stress-strain curve in uniaxial compression
b) Stress-relaxation at different strain levels
c) Trabecular thickness at increasing strain
d) Trabecular separation at increasing strain
e) Degree of Anisotropy of increasing strain