Regional Differences in Mechanical and Material Properties of Femoral Head Cancellous Bone in Health and Osteoarthritis

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Abstract. Osteoarthritis (OA) is a debilitating condition common among the aging population. In this study we have determined mechanical and material properties of cancellous bone cores from two differently loaded regions of femoral heads obtained from healthy subjects and those with end-stage osteoarthritis. Densitometric properties were determined prior to compression testing for Young’s modulus (E<sub>C</sub>) and yield strength (σ<sub>y</sub>), after which bones were powdered for analysis of collagen and mineral content. In both OA and normal cancellous bone, volumetric bone mineral density (BMD<sub>v</sub>), apparent density (ρ<sub>a</sub>), E<sub>C</sub>, and σ<sub>y</sub> were systematically greater in the superior than in the inferior region (P < 0.05). In the OA inferior region, median BMD<sub>v</sub> (0.434 g-cm<sup>-3</sup>) and ρ<sub>a</sub> (0.426 g-cm<sup>-3</sup>) were significantly greater than in normals (0.329 and 0.287 g-cm<sup>-3</sup>, respectively, both P < 0.05) reflecting an increased amount of tissue. The mineral:collagen ratio was decreased in OA, but this was only significant in the superior region (P < 0.008). Relationships between E<sub>C</sub> and both BMD<sub>v</sub> and ρ<sub>a</sub> were weaker in OA bone cores (r<sup>2</sup> = 0.66 and r<sup>2</sup> = 0.59) than in normals (r<sup>2</sup> = 0.86 and r<sup>2</sup> = 0.77, respectively). Likewise, σ<sub>y</sub> and both BMD<sub>v</sub> and ρ<sub>a</sub> were weaker in OA (r<sup>2</sup> = 0.74 and r<sup>2</sup> = 0.70) than in normals (r<sup>2</sup> = 0.83 and r<sup>2</sup> = 0.77, respectively). For the same value of density measure, E and σ<sub>y</sub> tended to be lower in OA bone when compared with normal bone. In conclusion, femoral head cancellous bone mass in end-stage osteoarthritis is increased but undermineralized, and is neither stiffer nor stronger than normal cancellous bone.

Key words: Compressive modulus — Cancellous bone — Osteoarthritis — Femoral head — Bone density

Osteoarthritis (OA) is a debilitating condition that commonly affects the major weight-bearing joints of the body. Chronic degeneration of both articular cartilage and underlying bone results in pathological changes that adversely affect the function of the joint. Whether or not bone changes precede or follow changes in the soft tissues [1], osteoarthritis has generally been considered a disorder of chondrocyte function and much work has focussed on describing the pathological changes to cartilage and the articular surface of the joint.

The inverse relationship between osteoarthritis and osteoporotic fracture has been recognized for many years [2], although this remains controversial. Osteoporosis is associated with low areal bone mineral density (BMD) and is rarely found in patients with osteoarthritis and vice versa [3]. Clinical studies have reported relatively high BMD in osteoarthritis at various skeletal sites including those remote from the affected joint [4]. Reduced osteoporotic fracture risk in OA is likely to be due to the preservation of bone mass, although the mechanical competence of OA bone throughout the progression of the disease is uncertain. Bone stiffening may occur in the early stages of OA in humans and primates [5] as originally hypothesized by Radin et al. [6], although in other animal models evidence of early trabecular changes are inconsistent.

Alterations in mechanical properties may be associated with changes in the composition of the bone matrix. Studies of trabecular bone sampled from femoral heads with end-stage OA indicate that at this advanced clinical stage the matrix of trabecular bone has marked quantitative and qualitative differences from both healthy and less severely affected bone. Overall, biochemical analyses suggest that turnover of bone matrix in OA is increased [7–9] and that this is associated with alterations to the structure of the trabecular network [10] which is undermineralized [7, 11, 12].

In order to more clearly define some of the material and mechanical properties of OA bone, we have compared density, porosity, compressive modulus, and yield strength in trabecular bone from the femoral head taken at surgery from patients with end-stage OA with that taken from healthy subjects at autopsy. Furthermore, to

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Table 1. Summary of age and gender of femoral head samples

<table>
<thead>
<tr>
<th></th>
<th>Osteoarthritis</th>
<th>Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td>7 m, 11 f, 3 unknown</td>
<td>5 m, 6 unknown</td>
</tr>
<tr>
<td>Median age (yrs)</td>
<td>65</td>
<td>71</td>
</tr>
<tr>
<td>(age range, yrs)</td>
<td>(55–89)</td>
<td>(67–89)</td>
</tr>
</tbody>
</table>

discriminate changes at different locations within the femoral head, two sites were sampled which experience markedly different loading patterns [13, 14].

Materials and Methods

Sixty-two femoral heads were obtained either at post mortem or post-operatively and were stored frozen in sealed containers. Thirty, 30 were excluded from the study due to either the presence of other bone-related disorders (n = 21) or damage to the cancellous bone within the regions of interest (n = 9). Of the remaining 32 femoral heads, visual and radiographic inspection showed the typical features of end-stage osteoarthritis in 21 bones (20 of which were obtained at surgery). These features included cartilage fibrillation with erosion, subchondral bone thinning, osteophyte growth and femoral head deformation. This diagnosis was confirmed by clinical records (where available), and the samples were classified as OA. The remaining 11 samples, all of which were obtained at autopsy, had none of these features and were classified as normal. The age and gender characteristics of the samples, where known, are given in Table 1. For the collection of tissue samples informed consent was given by either the patients or their next of kin. The study was carried out in accordance with the Declaration of Helsinki.

Sample Preparation

Using a band saw, a bone section (approx. 16 mm thick) was cut which was orientated along the coronal plane of the proximal femur and incorporated the fovea. Care was taken to ensure that the surfaces of the section were cut parallel to one another, however, these surfaces were not machined parallel. Machining removes damaged material from the cut surfaces, minimizing imperfections that may influence the measurements made by the unconstrained compression tests. From this section, cores (12 mm in diameter) were drilled out along the anterior-posterior axis from the inferior and superior regions, as previously defined [15] and illustrated in Figure 1. The lengths and diameters of the cores were measured using vernier calipers (error in measurement ± 0.05 mm) and their gross volumes were calculated. Bone cores were wrapped in cotton wool soaked in PBS and stored frozen in sealed tubes.

Physical Measures

The trabecular bone cores, each approximately 12 × 16 mm, were laid on their sides and bone mineral content (BMC) was measured in air by dual energy X-ray densitometry (DXA) using a Hologic QDR 1000/W bone densitometer. The error in the precision of this measurement was < 5%. The lumbar spine scanning protocol was used which has a raster resolution of 1 mm × 1 mm. After this, each core was water-jetted and vacuum de-gassed to remove fat and nonadherent soft tissue. After a brief defatting step with trichloroethylene, true trabecular volume was determined using a water displacement method based on Archimedes’ principle [16]. Hydrated tissue weights were measured after removal of the free water by centrifugation at 1500 g for two periods of 1 min and 15 min, in tubes containing blotting paper [17, 18]. From weight and volume measurements, apparent (or structural) density, true (or material) density, and porosity were calculated using equations 1, 2, and 3, respectively.

\[
\text{Apparent (structural) density} = \frac{\text{hydrated tissue weight}}{\text{gross volume}}
\]

\[
\text{True (material) density} = \frac{\text{hydrated tissue weight}}{\text{trabecular volume}}
\]

\[
\text{Porosity} = \left(1 - \frac{\text{trabecular volume}}{\text{gross volume}}\right) \times 100\%
\]

Unconfined compression tests were performed using a materials testing machine (E.S.H. Model 4798, Brockley, UK) interfaced to a personal computer using a 12-bit A/D converter allowing load and displacement values to be saved for future analysis. Bone cores were compressed at a constant deformation rate of 0.25 mm min⁻¹. Young’s modulus of compression (E_c) was derived from the slope of the linear part of the load-displacement curve. Yield strength was calculated from the point where the slope of the load-displacement curve reached its maximum value. For this purpose, the differential of a polynomial equation fitted to the load-displacement curve was used [19].

Chemical Measures

After mechanical testing, each bone sample was prepared for biochemical analyses. Bone cores were powdered in a precooled Spex 6700 impaction mill (Spex Ind., USA) under liq-