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The effect of strain rate on the failure stress and toughness of bone of different mineral densities

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ABSTRACT

The risk of low energy fracture of the bone increases with age and osteoporosis. This paper investigates the effect of strain rate and mineral level on the peak stress and toughness of whole ovine bones.

40 fresh ovine femurs were subjected to 3-point bending at high ($17.14\ s^{-1}$) and low ($8.56\times10^{-3}\ s^{-1}$) strain rates with or without a controlled amount of demineralisation. Mineral removal was achieved by ultrasonically assisted exposure in Ethylene diamine tetra-acetic acid (EDTA). The ultimate stress for whole bones of normal mineral content was 200 MPa at the high rate of strain and 149 MPa at the low rate of strain.

With changes in bone mineral levels such as may occur in osteomalacia and osteoporosis, the change in toughness varied at different strain rates; a mean value of $3.7\pm1.4\ MJ/m^3$ was obtained for the toughness of normal quality whole bone tested at slow loading rate and a reduction of approximately 25% was observed in the demineralised whole bone specimens at the slow loading rate (mean $2.8\pm0.9\ MJ/m^3$). When tested at the high loading rate there was a negligible difference in the toughness between the two ($2.0\pm0.6\ MJ/m^3$) mineral levels.

This indicated that there was a strain rate dependant effect for the mineral density, and that the removal of mineral alone did not explain all of the reduction in mechanical properties that occur with age or disease. Thus, the reduction in mechanical properties at high strain rates was likely to be due to other phenomena such as increased porosity or reduced collagen quality, rather than loss of mineral.

With decreasing mineral levels, as measured by DEXA in clinical practice, the increased fracture risk is dependent on the velocity of the impact. Thus the estimates of increased fracture risk given clinically for a lower DEXA value should be different for high and low energy injuries.

1. Introduction

Bone is a hierarchical composite material and changes occur on multiple length scales that influence the mechanical properties of the whole bone. The risk of low energy fracture of the bone increases with age and osteoporosis. Martin (2003) and Van der Meulen et al. (2001) indicated that there are many factors that combine to give bone its overall quality. However, the onset of the effects of osteoporosis is determined by assessing the mineral content of the bone (Kanis, 1994).

Shah et al. (1995) conducted bending tests on feline bone segments that had been demineralised to different degrees. However, these were tested with a machine crosshead speed of 10 mm/min, which is considerably slower than that would be encountered in physiological activities such as walking. The viscoelastic response of demineralised bone was acknowledged in a study by Sasaki and Yoshikawa (1993) who investigated the stress relaxation of demineralised bone, but they used samples of bone machined from bovine femur rather than whole bones and tested these by cantilever bending. To date, no studies have investigated the effect of partially demineralised bone at traumatic loading rates.

Therefore the aim of this research is to investigate the effect of partial mineral removal from bone to a clinically relevant level on the ultimate stress and the toughness at both low and fast strain rates. The strain rates in this study have been chosen to be representative of (i) the lower end of fractures classed as “low energy fractures”, i.e. those that could occur from a fall from a bed or chair or a fracture that occurs due to movement before the fall, which has been estimated to be just under 10% of elderly hip fractures (Cummings and Nevitt, 1989), (ii) those found to be representative of high energy fracture, such as the rates of strain that have been measured to occur in the lower limbs during a motor vehicle accident (Hansen, 2008). In particular, as bone is a viscoelastic multidimensional composite, we tested the hypothesis that alteration of the composition of this composite will have differing effects at different rates of strain.

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2. Methods

A total of 40 femurs were harvested from freshly euthanized sheep. These were split equally between four testing groups according to testing speed and mineral content; fast-normal (FN), fast-demineralised (FD), slow-normal (SN), slow-demineralised (SD).

2.1. Testing

The slow loading rate experiments were carried out on a commercially available mechanical testing machine, Zwick/Roell z005 (Zwick GmbH & Co, Ulm, Germany). Data capture was provided by TestXpert V9.01 (Zwick GmbH & Co, Ulm, Germany). This is the proprietary software for the Zwick and as such acted as both the data capture and the control system for the slow rate experiments.

The bones were loaded in 3-point bending at a constant rate of 1 mm/s. This created an average strain rate in the bone of $8.56\times10^{-3}\ s^{-1}$ ($\pm1.42\times10^{-3}$ SD).

The fast rate loading was applied in 3-point bending by a custom designed experimental set up. The final set up consisted of: a bespoke manufactured bone holder, an aluminium impact head, a dynamic force sensor (PCB 208C05 (PCB Piezotronics Inc. New York, USA)), a pneumatic actuator (Norgren PRA/18200/200) and a LabVIEW data capture system (National Instruments Corporation. Texas, USA) sampling at 100 kHz to monitor the loading. A Vision Research Phantom v7.1 monochromatic high speed camera (Vision Research Inc. New Jersey, USA) running at 25,000 fps and fitted with a Nikon 24–85 mm F2.8 lens was used to record the deformation at the high loading rate.

The initial rate of displacement of the unloaded actuator was 3.6 m/s ($\pm$0.2 m/s). As the mass of the actuator was constant, the initial energy imparted was comparable. The strain rate that was subsequently produced in the bone through bending was dependant on the stiffness of the bone; the normal bone quality specimens had a mean strain rate of 13.3 s^{-1}($\pm$7.0 SD) and the demineralised group was found to have a mean strain rate of 20.9 s^{-1}($\pm$7.7 SD). This gave an average strain rate of 17.14 s^{-1} ($\pm$8.20 SD) for the fast loading rate experiments. Although the strain rates experienced by the bone in these tests varied significantly, even the minimum strain rate encountered in these experiments was three orders of magnitude greater than that found to occur during extreme physiological loading, such as up-hill running as found by Burr et al. (1996).

During testing at both loading rates the bone was located on rounded supports of 10 mm diameter at either end and the load was applied via an aluminium cylinder with a diameter of 35 mm. The bone was positioned and the supports adjusted as required to ensure the supports were located consistently between samples. The area immediately distal to the lesser trochanter and the flat section of bone proximal to the posterior femoral condyles were chosen as this would ensure the supports were located consistently and on a section of bone that would prevent rotation of the bone during loading. The load was always applied equidistantly from the two supports. The experimental set up can be seen in Fig. 1. The second moment of area was derived at several cross sections along the length of the bone using images taken from post testing microCT scans. The second moment of area at either side of the fracture was averaged to provide a value for this property at the fracture site to be used when determining the stress.

Peak stress was calculated using engineers bending theory using the bending moment due to peak force and the second moment of area derived as described above. Due to the low aspect ratio, the length of the tested span divided by the depth of a whole femur and the use of 3 point bending during testing it was required to account for deflection due to shear by using Timoshenko's bending theory. The normal (bending) strain was then calculated and used to plot a stress–strain curve. The toughness was found by from the area under the curve.

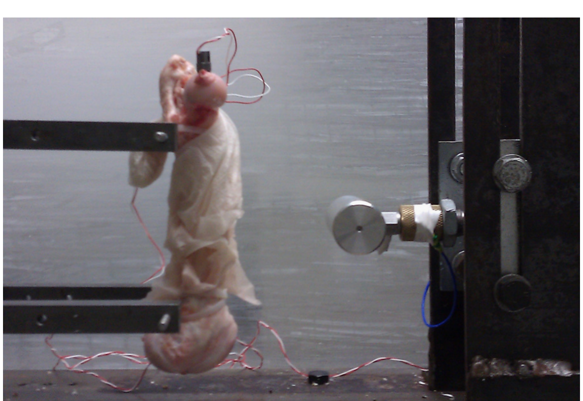

Fig. 1. Experimental setup for fast loading rate tests. Bone shown wrapped in gauze to prevent dehydration prior to testing.

2.2. Demineralisation

In order to examine the effects of the bone mineral on the bone properties, half of the bones were subjected to a standardised amount of demineralisation. The level of demineralisation was assessed using a calibrated step wedge in the radiographic image (Dawson et al., 2008) and mean values of 2.47 g/cm^3 ($\pm$0.42 SD) were found for the normal quality group and 1.86 g/cm^3 ($\pm$0.28 SD) for the demineralised group, representing a mean reduction of 25%. This mineral density reduction is representative of a density reduction that a 75 year old female may have undergone compared to her peak bone density (Kanis, 1994). To speed up the decalcification process, mineral was removed by ultrasonically assisted agitation in 10 M Ethylene diamine tetra-acetic acid (EDTA). This is a validated method that has been used in previous studies (Shah et al., 1995) and is commonly used as a means of preparation of bone samples for histology (Alers, 1999). It has been shown not to cause morphological deterioration of the tissue (Thorpe, 1963; Milan, 1981). Additionally, the ultrasonic agitation was thought to assist the removal of mineral from within the bone. The reduced grey level throughout the whole cross section of the bone on the microCT images confirmed that the mineral dissolution was not confined to the external surfaces.

In order to ensure that the porosity was not altered during demineralisation, 8 sample fragments from 4 paired limbs (normal and demineralised) were scanned at a resolution of 4.8 μm. Analysis of these groups revealed mean porosities of 8.15% $\pm$3.13 SD and 7.88% $\pm$3.76 SD for the normal and demineralised specimens respectively, which represented no significant difference between the groups as found by a paired *t*-test with a *p* value of 0.924.

2.3. Data analysis

The data was checked for normality before an analysis of variance (ANOVA) was performed with a Tukey simultaneous test to investigate the differences between the groups for statistical significance. A *p*-value equal to or less than 0.05 was taken to indicate a statistically significant difference.

3. Results

The results from the experiments performed for this study are presented in Table 1 and Fig. 2.

Statistically significant differences ($p<0.05$, ANOVA) were found between the fast loaded normal quality group and all the other groups when comparing the peak stress. No further statistical differences were found. Statistically significant differences ($p<0.05$, ANOVA) were found for the toughness at failure between the slow loaded, normal quality bones and both qualities of fast loaded bones.

The results highlight the involvement of the mineral in preventing fracture from traumatic loading by demonstrating a decrease in peak stress when demineralised bone was loaded at a fast rate of strain. However, the very similar mean values and standard deviations for toughness for normal and low mineral levels at the high rate of strain was interesting as this implied that the mineral did not play a significant role in the toughening mechanism at rates of strain encountered in high velocity trauma.

4. Discussion

4.1. Tests at normal mineral levels

Bones of normal density from healthy young adult animals were found to have a higher peak stress but a lower toughness when loaded at a fast strain rate.

Table 1
Mean ($\pm$SD) of peak stress and failure toughness of tested bones.

	FD	FN	SD	SN
Peak stress, σ_{ult} (MPa)	141$\pm$17.6	201$\pm$19.9	136$\pm$23.9	148$\pm$32.2
Toughness, T (MJ/m^3)	2.0$\pm$0.6	2.0$\pm$0.6	2.8$\pm$0.9	3.7$\pm$1.4