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# Density and temperature effects on some mechanical properties of cancellous bone

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## INTRODUCTION

The mechanical properties of cancellous bone are of interest to clinicians because mechanical failure of cancellous bone is one of the commonest causes of pain and immobility in the elderly. There has recently been a great deal of interest in the relationship between the mechanical properties of bone and various factors that might affect them. Of particular concern has been the assertion by Carter and Hayes (1976, 1977) that the Young's modulus of cancellous bone is proportional to the cube of the apparent density, and the compressive strength proportional to the square of the apparent density. (Apparent density is the mass of bone material in a volume of cancellous bone, the volume being calculated from the external dimensions of the block of material.) Hypotheses concerning the process of remodelling make use of these supposed power law relationships (Carter *et al.*, 1987). The relationship has been examined in a variety of cancellous bone types and, in general, it has been found that the exponents of the relationship are not as high as Carter and Hayes found. In particular, Rice *et al.* (1988) have conducted a comprehensive survey of the literature, and claim that this suggests that both Young's modulus and strength are proportional to the square of the apparent density. Gibson (1985) has attempted to relate the exponents found in the literature with a set of models describing how cancellous bone should deflect and fail when it has various different densities. The relationship seems to hold even though the actual arrangement of the trabeculae in relation to the loading axis is ignored. Of course the architecture, or fabric, of the bone will also affect the mechanical properties, a question that is being addressed in several laboratories.

It is convenient, of course, to test the mechanical properties of bone at room temperature, and the great majority of tests on cancellous bone have been conducted at room temperature. However, it is quite possible that the properties are rather different at blood temperature. It is necessary, therefore, to determine whether variation of temperature between about 21 and 37°C produces important differences in the mechanical properties.

The purposes of the present paper are threefold.

(1) To add information to the discussion concerning the value of the exponent for Young's modulus and strength as a function of apparent density.
(2) To determine the effect of apparent density on the work that must be done on a specimen up to the point that it achieves the highest load it can bear, and on the strain at this load.
(3) To determine the effect of variations in temperature on these mechanical properties.

## MATERIALS AND METHODS

A bovine femur was obtained from a butcher. The distal condyles were sawn into rectangular columns of sides somewhat greater than 10 mm. These columns were themselves sawn into cubes, and these rough cubes ground to cubes of sides that varied from 9.9 to 10.6 mm. All opposite faces were parallel. The specimens were kept wet while these operations took place. The 62 specimens were assigned randomly to two roughly equal-sized groups. All members of each group were then tested at either 20–22°C or 37°C, in a water bath. The specimens were loaded in compression between the parallel faces of an 1122 Instron table testing machine. The compliance of the testing rig was determined by loading it against itself, and account was taken of the compliance during subsequent calculations.

Cancellous bone loaded in compression characteristically shows a load increasing with deformation until a maximum is reached. The load then decreases slightly, and there is a long region of increasing deformation with little change in load. Finally the specimen becomes compacted, and the load starts to rise sharply to high values. However, this latter increase is not relevant to the clinical situation. The specimens were loaded at a head speed of 1 mm $min^{-1}$ and the deformation increased until the first maximum load was reached and the load started to decrease.

Linde and Hvid (1987) and Linde *et al.* (1988) have produced evidence that the measured mechanical properties of cancellous bone may change considerably after a prior 'conditioning' load. Our specimens were not given a conditioning load because, although the measured properties of cancellous bone may change after a conditioning load, we considered it more appropriate to measure the properties as they might be shown in a single catastrophic load, and as had been measured by most other investigators.

The mechanical properties determined were Young's modulus of elasticity, taken from the steepest part of the load deformation curve, the greatest stress (that is the stress at the *first* maximum in the load) the strain at the greatest stress, and the work done on the specimen up to the point where the greatest stress occurred, measured from the area under the load/deformation curve, and divided by the volume of the specimen.

The fat was removed from the specimens by subjecting the cube to a high speed jet of water for about five minutes, then holding a compressed air supply against one face, and repeating this process until no yellow patches appeared on the specimen surface on treatment with compressed air. The specimens were then tumbled overnight in a great excess of a chloroform/methanol



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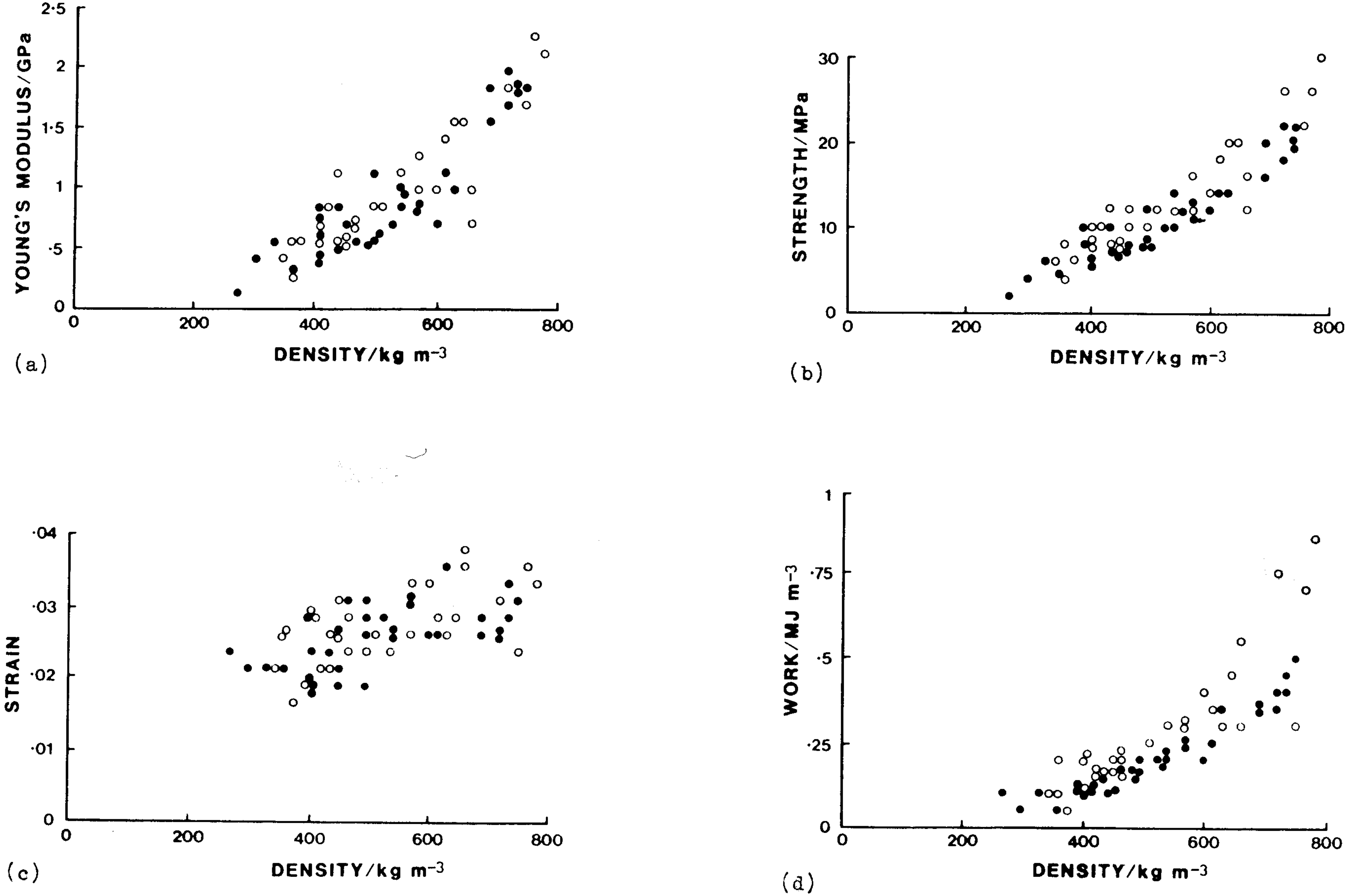


*Fig. 1. Scatter diagrams showing the relationship between apparent density (in kg $m^{-3}$) and various mechanical properties. The specimens tested at the lower temperature are represented by open circles, those tested at 37°C by solid circles.*
*(a) Young's modulus (GPa)*
*(b) Compressive strength (MPa)*
*(c) Strain*
*(d) Work to highest load (MJ $m^{-3}$)*

mixture, dried at 70°C and weighed. The tumbling in solvent was repeated (usually once only) until the weight remained unchanged. We cut into some of the specimens, and could see that this procedure had removed the fat and other soft tissue.

## RESULTS

Figure 1(a, b, c, and d) shows the relationship between the four mechanical variables and apparent density, each point being symbolised as hot or cold. Table 1 is a summary of the statistical analysis. We discuss in turn the general relation between density and the various mechanical properties, and determine whether temperature has any effect on the mechanical property. Some of the relationships are clearly non-linear, so we also convert the mechanical variable and density to their logarithms, to see whether a power law relationship provides a better fit. Anyhow, the relationships discussed by Carter and Hayes (1977) were power law relationships, so it is necessary to convert to logarithms to compare our results with theirs.

### Young's modulus

Figure 1(a) shows that (as is also true of strength and work) the value of Young's modulus increases sharply with apparent density. The general distribution is not obviously non-linear, and the statistical analysis shows that a linear model produces as good a fit, as indicated by the value of $R^2$, as the power law model. However, the linear model predicts a very large and significant negative value ($t = 6.2$, $P \ll 0.001$) for Young's modulus at zero density, so a power law model is to be preferred. The values of apparent density in the specimens tested here vary by a factor of about three, and the values of Young's modulus by a factor of about twelve. Equation (6) indicates that the power law relationship between Young's modulus and density has an exponent of 1.87, less than the cubed relationship found by Carter and Hayes. However, Rice *et al.* (1988) found that the relationship more generally found in the literature was quadratic, to which, of course, 1.87 is quite close.

Analysis of the relationship between apparent density and Young's modulus either ignoring temperature, or including it as a dummy variable, shows that tem-

*Table 1. Various equations for the relationship between the mechanical properties of cancellous bone, and apparent density and temperature. The values in brackets, under the equations, are the t values relating to the statistical significance of the coefficients. Youngs modulus in GPa, Strength in MPa, and Work per unit volume in $MJ\ m^{-3}$*

| | | |
|---|---|---|
| | **Young's modulus ($E$)** | |
| (Cold) | $E = -0.806 + 0.00342$ density | $R^2 = 0.76$ (1) |
| (Hot) | $E = -0.884 + 0.00344$ density | $R^2 = 0.80$ (2) |
| (Cold) | $\log E = -4.81 + 1.76 \log$ density | $R^2 = 0.76$ (3) |
| (Hot) | $\log E = -5.41 + 1.96 \log$ density | $R^2 = 0.80$ (4) |
| (Both) | $E = -0.811 + 0.00343$ density $- 0.0674$ temp<br>(6.2) (14.8) (1.1) | $R^2 = 0.78$ (5) |
| (Both) | $\log E = -5.13 + 1.87 \log$ density $- 0.042$ temp<br>(6.1) (14.6) (1.5) | $R^2 = 0.78$ (6) |
| | **Strength ($S$)** | |
| (Cold) | $S = -10.5 + 0.045$ density | $R^2 = 0.83$ (7) |
| (Hot) | $S = -8.69 + 0.038$ density | $R^2 = 0.88$ (8) |
| (Cold) | $\log S = -3.67 + 1.75 \log$ density | $R^2 = 0.85$ (9) |
| (Hot) | $\log S = -3.83 + 1.79 \log$ density | $R^2 = 0.88$ (10) |
| (Both) | $S = -8.68 + 0.041$ density $- 1.63$ temp<br>(6.9) (18.3) (2.8) | $R^2 = 0.85$ (11) |
| (Both) | $\log S = -3.73 + 1.77 \log$ density $- 0.059$ temp<br>(15.7) (20.1) (3.0) | $R^2 = 0.87$ (12) |
| | **Strain at highest load ($\varepsilon$)** | |
| (Cold) | $\varepsilon = 0.015 + 0.000024$ density | $R^2 = 0.35$ (13) |
| (Hot) | $\varepsilon = 0.016 + 0.000020$ density | $R^2 = 0.30$ (14) |
| (Cold) | $\log \varepsilon = -2.81 + 0.46 \log$ density | $R^2 = 0.33$ (15) |
| (Hot) | $\log \varepsilon = -2.65 + 0.39 \log$ density | $R^2 = 0.30$ (16) |
| (Both) | $\varepsilon = 0.016 + 0.000022$ density $- 0.0015$ temp<br>(7.4) (5.6) (1.4) | $R^2 = 0.34$ (17) |
| (Both) | $\log \varepsilon = -2.71 + 0.42 \log$ density $- 0.022$ temp<br>(12.9) (5.5) (1.3) | $R^2 = 0.33$ (18) |
| | **Work per unit volume ($W$)** | |
| (Cold) | $W = -0.383 + 0.00106$ density | $R^2 = 0.74$ (19) |
| (Hot) | $W = -0.239 + 0.00086$ density | $R^2 = 0.89$ (20) |
| (Cold) | $\log W = -6.71 + 2.25 \log$ density | $R^2 = 0.80$ (21) |
| (Hot) | $\log W = -6.31 + 2.06 \log$ density | $R^2 = 0.88$ (22) |
| (Both) | $W = -0.268 + 0.00106$ density $- 0.0714$ temp<br>(6.2) (13.7) (3.6) | $R^2 = 0.77$ (23) |
| (Both) | $\log W = -6.43 + 2.14 \log$ density $- 0.11$ temp<br>(10.5) (17.8) (4.1) | $R^2 = 0.85$ (24) |

perature is just worth keeping as an explanatory variable. That is to say, the amount of variance explained increases when temperature is included, after allowance has been made for the concomitant reduction in the number of degrees of freedom (Cooper and Weekes, 1983, p. 192). Equation (6) suggests that increasing the temperature from 21 to 37°C has the effect of decreasing the value of Young's modulus by 7 per cent (antilog $-0.031 = 0.93$).

#### Strength

Figure 1(b) shows what appears to be a curvilinear relationship between strength and apparent density. The statistical analysis shows hardly any difference between the linear and the power law model in explanatory power. However, as with Young's modulus, the linear model predicts a quite large negative value of strength at zero apparent density; this value is highly significant, ($t = 6.9$, $P \ll 0.001$). This is a reason for supposing the power law model to be the better one. The exponent of the relationship between strength and apparent density is 1.77, which is reasonably close to Carter and Hayes' finding of a quadratic relationship. Gibson (1985) proposed, for theoretical reasons, that the relationship should be quadratic, and Rice *et al.* (1988) from a survey of the literature, also found a quadratic relationship.

The effect of temperature is statistically significant and quite strong; equation (12) suggests that increasing the temperature from 21 to 37°C reduces the strength by 13 per cent.

#### Strain at maximum load

Figure 1(c) shows the strain that the specimen undergoes by the time it reaches its maximum load increases with increasing density. The effect is statistically very significant (in equation (18), $t_{61} = 5.5$, $P < 0.001$) but is not very strong ($R^2 = 0.33$). Unlike the cases for Young's modulus and strength, it is not obvious that strain at maximum load *ought* to increase with apparent density. The relationship is reasonably linear, and the power law relationship is statistically very slightly weaker than the linear relationship. However, the linear model predicts a positive and highly significant positive strain at zero density, which indicates that it is not a very satisfactory model.

The effect of temperature, though statistically worth keeping in the model, is small. Equation (18) suggest that increasing the temperature over the experimental range reduces the strain at maximum load by 5 per cent.

#### Work per unit volume

Because strength increases with apparent density, and strain at maximum load does also, to some extent, it is not surprising that work per unit volume (which is a measure of the area under the stress–strain curve, which will itself, in general, be larger the larger the maximum stress and the larger the strain at maximum stress) is strongly dependent on apparent density. The scatter in Fig. 1(d) is markedly non-linear, and the linear equation (23) is a less good fit than the equivalent power law equation (24). The exponent for work, as a function of apparent density, is 2.14. This value is, satisfactorily, very close to the sum of the exponents for maximum stress and maximum strain (1.77 and 0.39, respectively).

The effect of temperature is both highly significant and large. According to equation (24), increasing the temperature over the experimental range reduces the work by 22 per cent.

### DISCUSSION

This work had three aims: to obtain additional estimates for the density-dependent exponents for Young's modulus and strength; to obtain new comparable data for strain at highest load and work to highest load; and to determine the effect of varying the temperature on these mechanical properties.

It must be emphasised that there are three intrinsic features of cancellous bone likely to affect its mechanical properties, and this study is concerned with one only: apparent density. The other two features are the mineral content of the bone material itself, and the architecture, or 'fabric' of the trabeculae. Preliminary studies in this laboratory indicate that mineral content does not vary sufficiently within the cancellous bone of a single bone to be an important cause of variability. However, fabric certainly can be important, as shown by, for example Goldstein (1987).

Nevertheless, work in our laboratory (in preparation) indicates only a very weak relationship between fabric and density; they are independently varying features, at least in relationship to their effect on mechanical properties. Therefore, variation in fabric will help to explain variation left unexplained after the effects of density have been removed. It is an additional, not an alternative, explanation of the variation; it is not considered in this paper.

#### Exponents for Young's modulus and strength

The value of the exponent obtained for Young's modulus, 1.87, is less than that obtained by Carter and Hayes (1977). There are various possible reasons for this. One is that our density values range only from 270 to 770 kg $m^{-3}$, and do not include the lower end of the range treated by Carter and Hayes. Nevertheless, the correlation coefficient is quite high, 0.88, so it is unlikely that adding points at the lower values for density would increase the value of the coefficient greatly, unless there were a marked non-linearity in the distribution, which is improbable, and not found by Carter and Hayes.

Another possibility concerns the fact that we are here trying to determine a *functional* relationship, that is, the actual relationship between Young's modulus or strength and density. The linear least squares relationships we have so far determined may be the best predictors of Young's modulus given a particular value of density, but do not give the best estimate of the form of the relationship. This is a complex matter, not yet fully resolved. However, a better estimate of the functional relationship for data like these, which have been transformed into logarithms, is probably given by dividing the exponent by the correlation coefficient, which produces the reduced major axis (Harvey and Mace, 1982; Rayner, 1985). In the present circumstances, because the correlation coefficient is so large, this has a rather small effect on the exponents, increasing that for Young's modulus from 1.87 to 2.12, (and that for strength from 1.77 to 1.89, bringing it quite close to the values of other authors who, it should be said, did not determine the functional relationship). The value for Young's modulus is still considerably less than the value of Carter and Hayes, but

*Table 2. These values are derived from equations (6), (12), (18), and (24) in Table 1*

| Property | Reduction in value of the property produced by increasing temperature from 21–22°C to 37°C (%) |
|---|---|
| Young's modulus | 7 |
| Strength | 13 |
| Strain at highest load | 5 |
| Work per unit volume | 22 |

close to the values found in the literature by Rice *et al.* (1988).

#### The effect of temperature

The effects of temperature are different for the different properties (Table 2). In the case of each property, increasing the temperature from 20 or 21 to 37°C reduces the value of the property significantly (though barely so in the case of Young's modulus). The higher temperature has the same kind of effect, though not nearly as strong, as a lower apparent density.

Because testing at body temperature and at room temperature does result in different values for the mechanical properties we have examined, it would obviously be good practice to test at body temperature. However, the actual differences are not very large, and are far less than those produced by differences in the apparent density of the specimens. For instance, temperature differences produce differences in work per unit volume of about 20–25 per cent, whereas there is a fifteenfold difference between the greatest and least values for this property in the present data set. The fact that these differences exist does, of course, have implications for the actual mechanisms controlling the mechanical properties of cancellous bone.

### SUMMARY

Sixty-two cancellous specimens from the distal femur of a cow were tested in compression, wet, either at room temperature or at 37°C. The mechanical properties tested were: Young's modulus, compressive strength, strain at greatest load, and work to greatest load per unit volume. All these values increased with apparent density of the specimen. The exponent 'b' in the equation: mechanical property = $k$ density$^b$ was 1.87 for Young's modulus, 1.77 for strength, 0.42 for strain at maximum load, and 2.14 for work. The effect of temperature is clear, though not very strong. Loading at 37°C rather than room temperature results in lower values for all the mechanical properties tested. However, the effects of temperature were not very great, the greatest effect being on work, which was decreased by 22 per cent.

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