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RELATIONS BETWEEN AGE, MINERAL DENSITY AND MECHANICAL PROPERTIES OF HUMAN FEMORAL COMPACTA

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Relations between mineralisation and mechanical properties have been investigated in human femoral compacta. Evidence of age-related changes in physical properties of bone, independent of mineral density, is provided by significant ($P < 0.05$) partial correlation between ultimate tensile stress and age. However, 75 per cent of variance in ultimate tensile stress, and 85 per cent of variance in ultimate compressive stress could be accounted for by variation in mineral density.

Key words: bone; mineral density; mechanical properties

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Bone mineral content (defined as the mass of mineral per unit bone length) at certain sites in long bones, is commonly measured *in vivo* either radiographically (Keane et al. 1959, Doyle 1961, Mayo 1961, Anderson et al. 1966) or by gamma-ray absorption techniques (Sorenson & Cameron 1967, West & Reed 1970, Mazess 1971, Shimmins et al. 1972). The mineral value constitutes a measure of bone size and degree of mineralisation, and is related to bone strength. However, assessment of skeletal ability to fulfil a structural role requires that mineral content be satisfactorily normalised with respect to physical size of the subject. The most frequently adopted "normalisation" procedure involves division of mineral content by a parameter of physical size, such as the total bone width or length. Extension of this method entails the acquisition of data concerning the general population (Smith et al. 1969, Mazess & Cameron 1973), and subsequent deduction of "normal" ranges of normalised mineral content for males and females within different age groups. Such data, necessary for direct clinical interpretation of mineral value, requires continual revision to account for changing populations. Moreover, even the normalised values of quantity of bone present do not reflect the mechanical properties of bone tissue; nor do they take account of the geometrical configuration of the bone. It is thus unlikely that such estimation alone will enable positive diagnosis of high susceptibility to fracture in more than a small percentage of cases.

In the present study, relations between mineral density, or mass of mineral per unit volume, and mechanical properties of human femoral compacta, have been determined. Essentially static tensile and compressive tests were conducted. Initial investigations showed that the strain rate employed was sufficiently rapid to ensure that "relaxation" of stress during testing did not significantly alter the effective rate of application of stress, although a limit of proportionality was attained at about 80 per cent of ultimate stress.

MATERIALS AND METHODS

Compact bone tissue from 27 human right femora, each excised post-mortem and stored at — 20° C until required, was studied. The bones were obtained from 13 male and 14 female cadavera ranging in age from 19 to 87 years.

The portion of femoral shaft extending approximately 10 cm toward the proximal extremity from about the bone midpoint was generally found to possess the greatest thickness of cortex, and was therefore designated as material for production of mechanical test pieces.

Preparation of tensile test pieces

At least one parallel sided plank of cortical bone with the long axis parallel to the femoral shaft was cut from each cross-sectional quadrant (delineated as illustrated in Figure 1) of each femoral portion. Cutting was carried out on the sliding table of a rotary blade macrotome equipped with parallel circular saw blades (Figure 2). Ringers' solution was employed as a coolant and lubricant. The resultant planks were 6 cm in length, 3.1 mm in thickness and with width corresponding to that of the bone cortex.

With the aid of hardened templates, each plank was quickly converted into a "waisted" tensile test piece (Figure 3 b) of minimum width 3.8 mm. Firstly, the plank was located between the two templates in the manner illustrated in Figure 3 a.

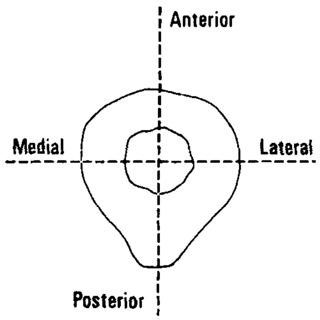

Figure 1. Delineation of femoral bone quadrants.

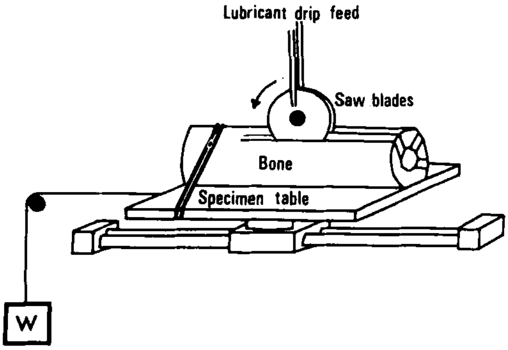

Figure 2. Macrotome sliding table arrangement.

Screws linking the templates were then tightened and the whole assembly was carefully clamped in a vice. Fine-toothed files were employed to reduce the protruding portions of bone, a half round file being used to shape the curved parts. The completed test piece was released, cleaned by brushing and by rinsing in water, and then sealed in a polythene bag and stored at — 20° C.

Preparation of compressive test pieces

Parallel-ended transverse sections of femoral shaft, 7.5 mm in length, were cut with the

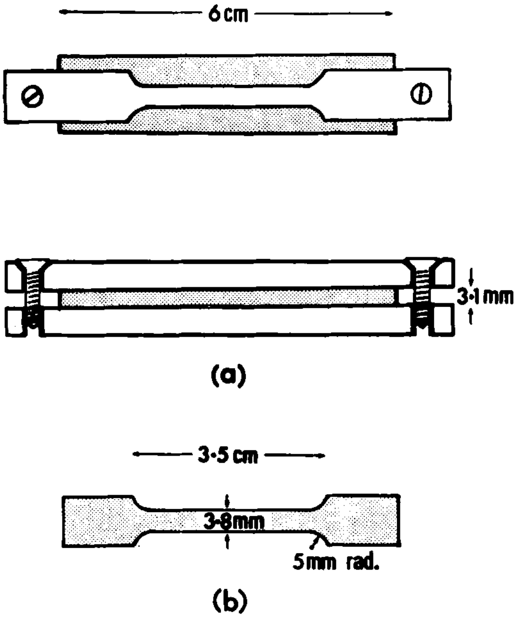

Figure 3. (a) Template production of tensile test piece. (b) Dimensions of completed test piece.

macrotome. Then, each section in turn was laid in a shallow trough containing Ringers' solution. Using a bench mounted drilling machine and a diamond tipped core drill, cylindrical compressive test pieces 5.1 mm in diameter and 7.5 mm in length, were removed from each cross-sectional quadrant. Finally, specimens were separately sealed in polythene bags and stored at — 20° C.

Measurement of mineral content of mechanical test pieces

Mineral content at the midpoint of the long axis of each mechanical test piece was measured with a specially constructed iodine-125 "miniature gamma ray absorptiometer". Specimens were scanned in a shallow water bath to standardise for varying organic content. The "K-value" parameter of mineral content defined by Shimmins et al. (1972) was evaluated from the dead-time corrected transmission data. This was converted to mineral content (mg/mm) using the calibration equation of Smith et al. (1974).

Specimen dimensions were determined precisely with a micrometer prior to resealing in polythene bags and storage at — 20° C.

Methods of mechanical testing

All specimens were removed from the deep freezer between 1 and 3 h before testing. During this time they remained sealed in the polythene bags and were allowed to attain room temperature without loss of moisture.

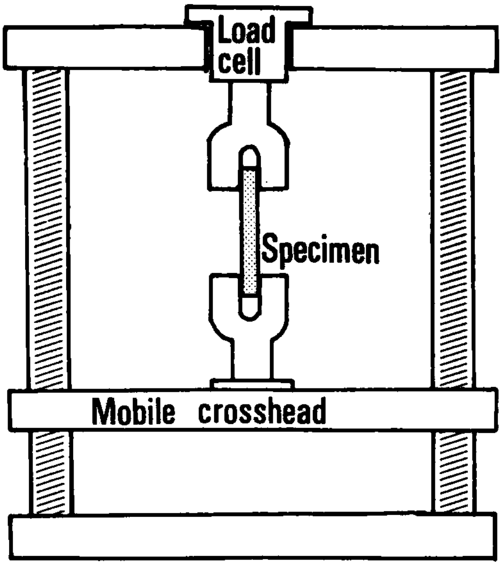

Figure 4. Experimental arrangement for tensile testing.

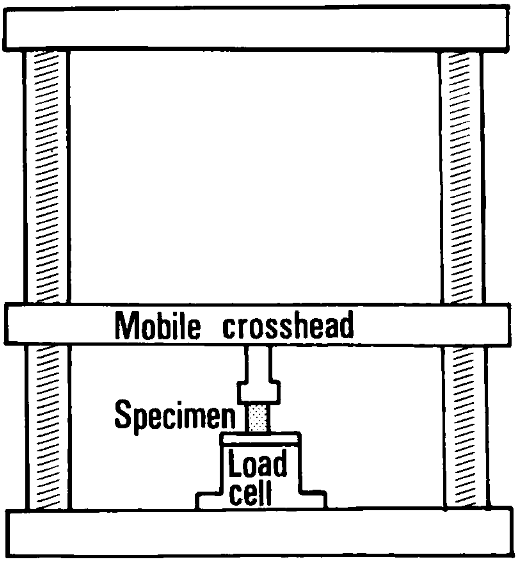

Figure 5. Experimental arrangement for compressive testing.

Tensile and compressive tests were conducted with an Instron Universal Testing Machine Model No. 1114. It comprises two vertical columns connected at top and bottom by rigid crossheads, each equipped with a mount facilitating load cell installation. Worm gears situated adjacent to both columns are used to vertically drive a mobile crosshead at predetermined velocity.

In order to carry out tensile tests, a load cell was mounted on the upper rigid crosshead. Test pieces were held by two wedge-type grips fixed to the load cell and mobile crosshead respectively (Figure 4). The mobile crosshead was then propelled downward at a rate of 2 mm/min. This produced a specimen strain rate of approximately 10^{-3} sec^{-1}. Each specimen was tested to destruction, load being monitored by a potentiometric recorder incorporated in the Instron control console.

For compressive testing, a load cell equipped with a flat anvil was mounted on the lower rigid crosshead, and a flat compression unit was attached to the underside of the mobile crosshead. Each cylindrical test piece in turn was placed on end in the centre of the anvil (Figure 5) and stressed to destruction by driving the mobile crosshead downward. The crosshead velocity of 0.5 mm/min produced approximately the same specimen strain rate as that which pertained during tensile testing. Load was once again monitored with the Instron recorder.

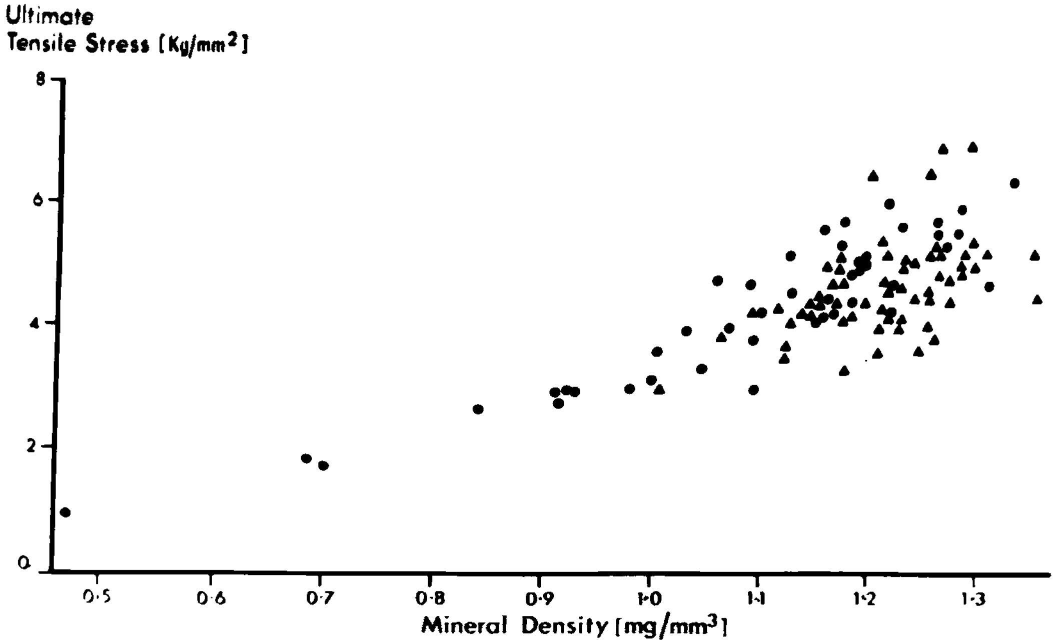

Figure 6. Ultimate tensile stress vs. mineral density.

RESULTS

Values of mineral content, tensile strength and compressive strength were each divided by specimen cross-sectional area to yield mineral density (M), ultimate tensile stress (σ_T), and ultimate compressive stress (σ_C). The latter two parameters were then considered in relation to the first. Good exponential correlation was found in both cases (Figures 6 and 7), producing correlation coefficients r = 0.87 and r = 0.92 respectively (Table 1).

Mineral density, ultimate tensile stress and ultimate compressive stress, of the different bone quadrants were each in turn compared using the Student's paired t-test. Generally, lowest values were found for specimens derived from the lateral/proximal quadrant, and highest values for those from the medial/anterior quadrant. Moreover, these two quadrants had significantly different ($P < 0.05$) tensile strengths and mineral densities, the respective algebraic mean discrepancies being 17.3 per cent and 7.6 per cent.

Table 1. Regression equations showing the relation of ultimate tensile and compressive stress to mineral density.

Relations between ultimate stress σ (kg/mm²) and mineral density M (mg/mm³)	No. of samples N	Correlation coefficient r	Index of determination r²
$\sigma_T = 0.524.e^{1.761.M}$	105	0.87	0.75
$\sigma_C = 0.547.e^{2.017.M}$	91	0.92	0.85

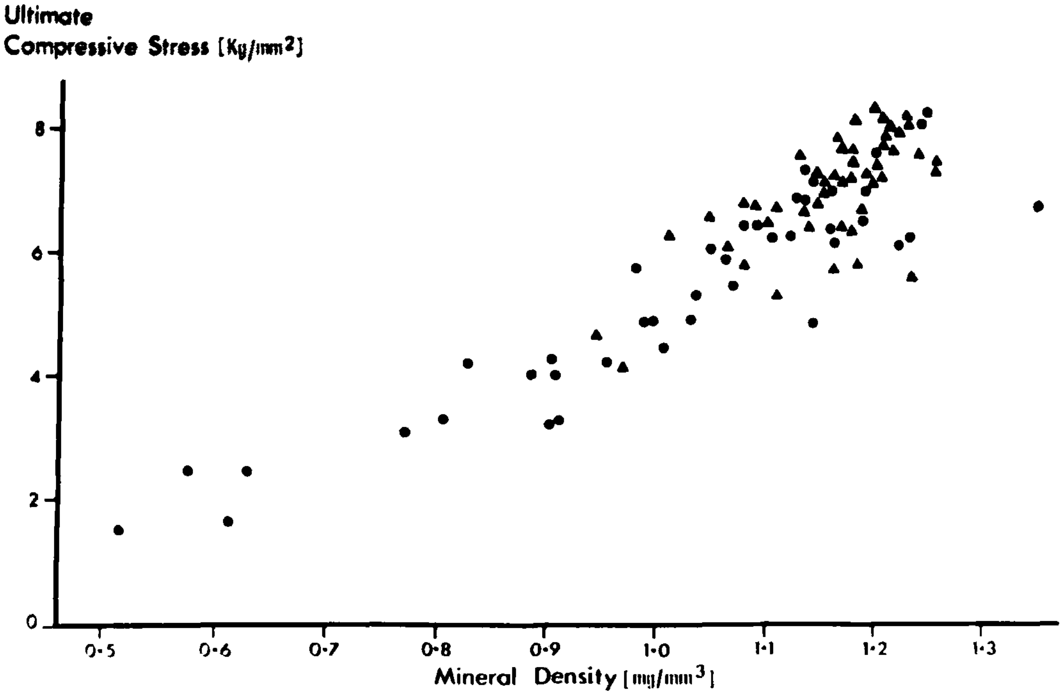

Figure 7. Ultimate compressive stress vs. mineral density.

In view of the differences between quadrants, average values of the parameters M, σ_T, and σ_C for specimens derived from all four quadrants were calculated: these values were considered with relation to age of the subject. Significant negative correlation of both average mineral density ($P < 0.05$) and average ultimate tensile stress ($P < 0.005$) with age was demonstrated (Table 2). Ultimate compressive stress did not change significantly with age ($P = 0.31$). Grand mean values calculated for all subjects studied were: $M = 1.21 \pm 0.04$ mg/mm³ (2 × S.E. of Mean), $\sigma_T = 4.62 \pm 0.39$ kg/mm², $\sigma_C = 6.28 \pm 0.50$ kg/mm².

Finally, partial correlation between ultimate stress, mineral density and age was considered. Coefficients of partial linear correlation are listed in Table 3.

DISCUSSION

Measured values of ultimate tensile and compressive stress are lower than those reported by some other researchers

Table 2. Regression equations showing the relation of mineral density and ultimate tensile stress, to age of the subject.

Relations between mineral density M (mg/mm³), ultimate tensile stress σ_T (kg/mm²), and Age A (years)	No. of samples N	Correlation coefficient r	Index of determination r²
$M = 1.37 - 0.0028.A$	25	−0.41	0.17
$\sigma_T = 6.47 - 0.0318.A$	24	−0.59	0.35

Table 3. Partial correlation of age, mineralisation and mechanical properties.

Nature of specimens	Coefficient of partial correlation rxy, # between variables x and y with third variable # held constant	Level of significance *P*
Tensile test pieces	$r_{\sigma M,A} = 0.76$	$< 5.10^{-4}$
	$r_{AM,\sigma} = 0.12$	n.s.
	$r_{A\sigma,M} = -0.47$	$< 5.10^{-2}$
Compressive test pieces	$r_{\sigma M,A} = 0.92$	$\cong 0$
	$r_{AM,\sigma} = -0.24$	n.s.
	$r_{A\sigma,M} = 0.15$	n.s.

n.s. = not significant.

(Dempster & Liddicoat 1952, Sedlin & Hirsch 1966, Melick & Miller 1966, Reilly et al. 1974). This may be attributed to the relatively low strain rate and to the fact that comparatively fresh bones have been studied.

The observed discrepancies between physical properties of different bone quadrants are broadly consistent with results published by Evans & Lebow (1951) and Evans (1964), with respect to sites in femur and tibia. The need to ensure consistency of anatomical origin when comparing bone samples from different subjects is emphasised.

It has been suggested that changes in size, orientation and distribution of mineral crystallites are associated with structural deterioration of the skeleton in old age (Chatterji & Jeffery 1968, Chatterji et al. 1972). Evidence supporting the concept of age-related changes in bone physical properties, unrelated to mineral density, is provided when age is considered as an independent variable (Table 3). Significant ($P < 0.05$) partial correlation with ultimate tensile stress is established for specimens derived from subjects ranging from 19 to 87 years of age. However, the regression coefficient is small and accounts for only a small part of the total data variance.

Total correlation and partial correlation of ultimate tensile stress, and ultimate compressive stress, with mineral density have been demonstrated (Tables 1 and 3). Indeed, 75 per cent of variance in ultimate tensile stress, and 85 per cent of variance in ultimate compressive stress, can be accounted for by variation in mineral density. This result is particularly important, demonstrating that mineral density was the major determinant of strength in compact bone specimens studied. Effects of variation in other physical properties of the collagenous bone matrix, or the mineral inclusions, must be either extremely small or, alternatively, be closely related to mineral density.

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