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BONE MINERAL CONTENT AND MECHANICAL STRENGTH OF THE FEMORAL NECK

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The bone mineral content of the femoral neck of 61 autopsy specimens was assayed by x-ray spectrophotometry. The mechanical strength of the specimens was also determined experimentally by applying a compressive force perpendicularly to the shaft. The ultimate force at fracture was obtained from force/displacement plots. A coefficient of correlation of 0.89 between bone mineral content of the femoral neck and the ultimate force at fracture was found. Even when limited to a group of women aged 67–80 a fairly close correlation was found. This indicates that the bone mineral level, measured *in vivo*, can be used as a criterion of the risk of fracture in elderly women.

Key words: femoral neck; mechanical strength; bone mineral content; x-ray spectrophotometry

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The incidence of fracture of the femoral neck in females doubles every 5 years after the age of 60, and the cumulative risk at the age of 80 is 7 per cent (Bauer 1960). The genesis of femoral neck fracture is unclear, but loss of bone mineral is often considered to be a significant factor.

The assay of bone mineral *in vivo* has previously been difficult. There has to be a loss of at least 30 per cent, and in some cases 50 to 60 per cent, of the calcium in the skeleton before rarefication can be established with certainty by the eye in routine radiography (Lachman 1955). This method is consequently very inaccurate. Using the x-ray spectrophotometric method, however, the bone mineral in the femoral neck can now be determined *in vivo* with a precision of 1.9 per cent (Gustafsson et al. 1974, Dalén & Jacobson 1974). The amount of bone mineral in the radiation beam is measured per unit area (mg/cm^2). The attenuation by the soft tissues is compensated for by using two different radiation energies. By scanning over a site, for example the femoral neck, the bone mineral content is obtained per unit length of the bone (mg/cm).

Since such direct measurements can be done it is of clinical interest to know to what extent the mechanical strength of the femoral neck can be assessed from the mineral content.

MATERIAL AND METHODS

Altogether 61 specimens, obtained from 54 women and 7 men, were studied. For 44 of the women the age range was 67–80 years.

The specimens were measured less than 5 h after autopsy while in a moist condition.

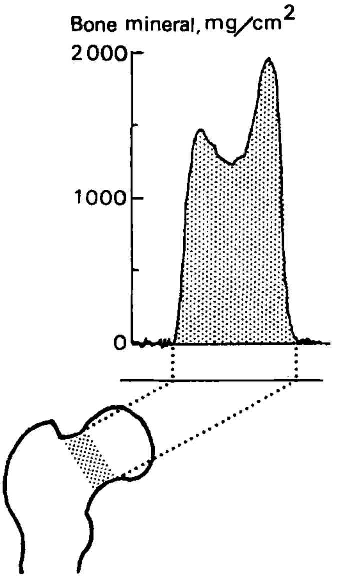

Figure 1. Distribution of bone mineral recorded by scanning perpendicularly to the femoral neck.

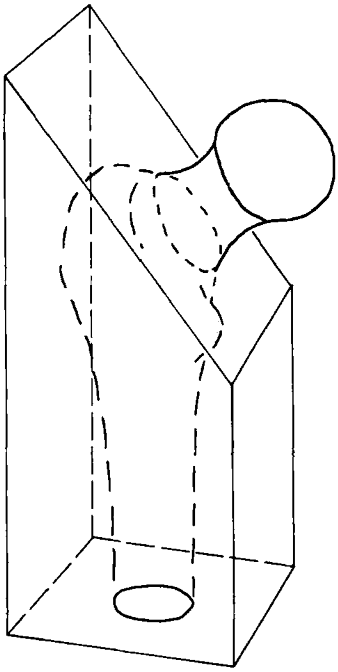

Figure 2. A plastic block moulded around the specimen leaving the neck and head free.

The bone mineral content was determined by the x-ray spectrophotometric method (Gustafsson et al. 1974). The femur specimen was scanned perpendicularly to the neck axis (Figure 1). The profile so obtained was used to determine bone mineral content (and two mechanical parameters, J and M, as defined in the appendix). The profile area is a direct measure of the bone mineral content per unit length of the scanned specimen.

The strength of the femoral neck was determined experimentally. A plastic block was moulded around the specimen (Figure 2) thereby supporting and preventing fractures in the lateral parts but leaving the neck and the head free. A compressive force was applied to the head perpendicularly to the shaft, with a speed of compression of 0.25 mm/s. The force was measured with a strain gauge, and the displacement of the head with a position gauge applied to the head by means of a separate mechanical transmission device. A plot was made of the force as a function of the displacement obtained (Figure 3).

RESULTS

Of the 61 specimens, 37 fractured at the medial part of the neck, and the lesions

Table 1. Coefficients of correlation between ultimate force, F_u, and four different mechanical parameters: Bone Mineral Content (BMC), BMC/Body weight, J and M. Correlations between bone mineral content and age are also given. For the parameters J and M, see appendix.

	Correlation ultimate force to four different mechanical parameters				Correlation age to BMC
	BMC	BMC Body weight	J	M	
All subjects	0.89	—	—	—	— 0.59
Women 67–80 years	0.78	0.78	0.71	0.71	— 0.02

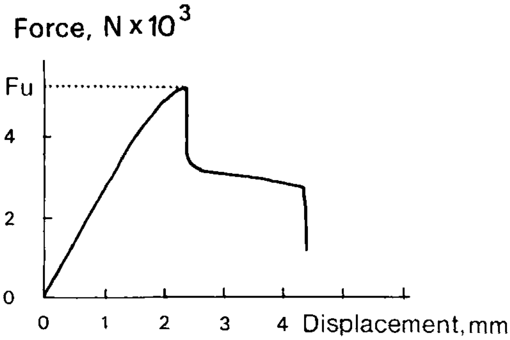

Figure 3. Typical force/displacement curve for the femoral neck. F_u denotes the ultimate force.

resembled clinical subcapital fractures. The rest of the specimens fractured in various other areas. There was no statistically significant association between the various types of fractures and the mechanical strength of the bone or the above-mentioned parameters.

A typical force/displacement curve is shown in Figure 3. The general appearance of the curves obtained is in agreement with those obtained by other investigators (Currey 1970, Simkin & Robin 1973). The ultimate force, F_u, fracturing the femoral neck is taken as the peak value for the curve. The mechanical strength of the specimen beyond this peak is due to the fact that an "impact fracture" was brought about.

The correlations between the ultimate force and the mechanical properties are presented in Table 1, as are coefficients of correlation between bone mineral content and age.

A plot of the ultimate force against bone mineral content for all the specimens is shown in Figure 4. The close correlation is not only due to the large age range of the material; this is apparent from the fact that there was no correlation between age and ultimate force fracturing the bones for women between the ages of 67 and 80 (Figure 5), whereas there was a correlation between the ultimate force and the bone mineral content for this age range (Figure 6).

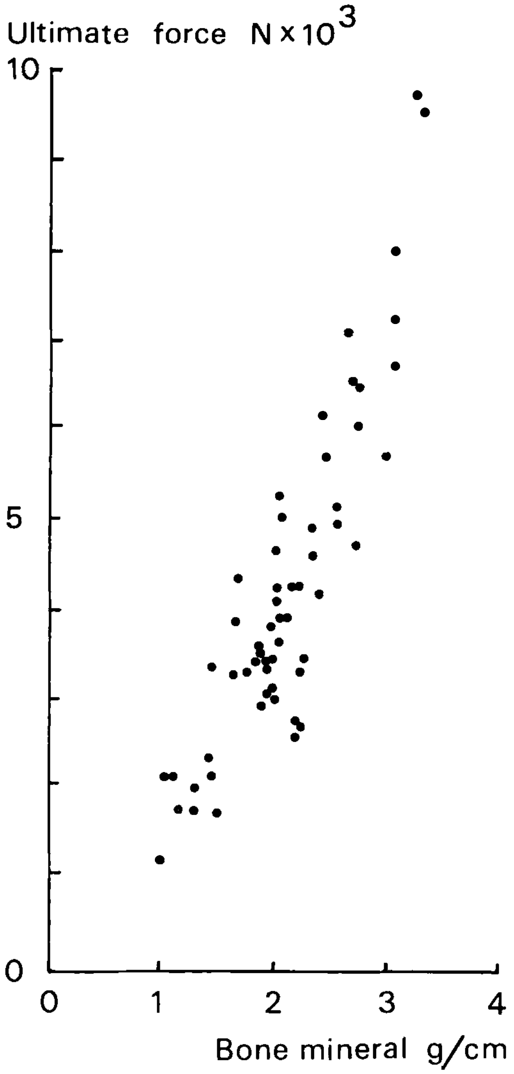

Figure 4. Ultimate force, F_u, as a function of bone mineral content for 51 women and 7 men, aged 31–93 years; r = 0.89.

DISCUSSION

Studies of the femoral neck related to this investigation have been published previously. Several investigators have reported a low bone mineral content or morphological signs of osteoporosis in patients with hip fractures (Alhave & Karjalainen 1973, Dequeker 1972, Foss & Byers 1972, Helelä et al. 1969, Stevens et al. 1962). Vose & Mack (1969) in an *in*

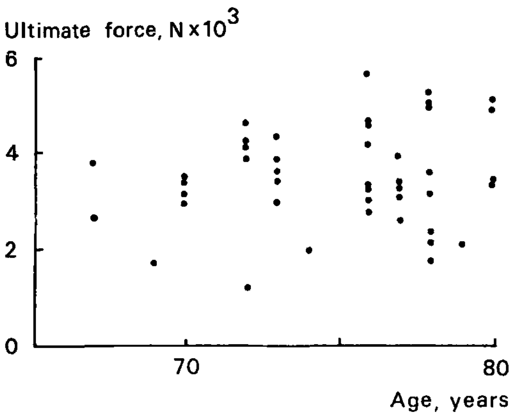

Figure 5. Ultimate force, F_u, as a function of age for 44 women, aged 67–80 years; r = 0.08.

vitro study found a positive correlation between the roentgenographic density and the mechanical strength of 10 femoral necks. Also, Schoenfeld et al. (1974) found a correlation (r = 0.70) between the compressive strength and the apparent density of cancellous bone in femoral heads. These studies show that the bone mineral content is of importance in the mechanical strength of the femoral neck. Phillips et al. (1975) developed a model to predict the failure load of femoral necks from measurements made on radiographs of the neck region.

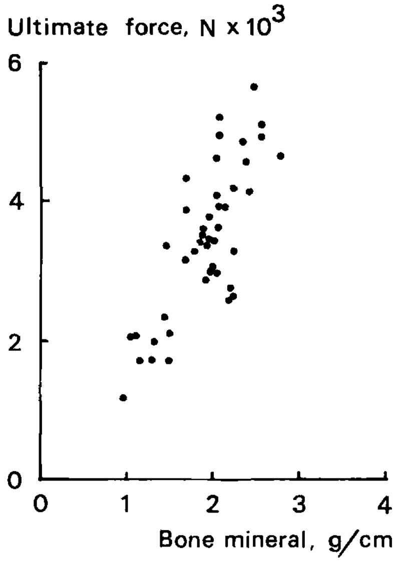

Figure 6. Ultimate force, F_u, as a function of bone mineral content for 44 women, aged 67–80 years; r = 0.78.

Many investigators have shown a close correlation between bone strength and bone mineral content, but they have usually not regarded the fact that both decrease with increasing age. It is therefore more interesting to know the correlation within a narrow age group where osteoporotic cases are likely to be found and where significantly high values of bone mineral contents do not appear and “improve” the results.

In this study, we have separately calculated the correlation between bone mineral content and mechanical strength for 44 women, aged 67–80 years. It is evident from the results that neither the mechanical strength nor the bone mineral content are correlated with age in this group, whereas the bone mineral content and mechanical strength are correlated with each other (r = 0.78).

The correlation found is not caused by varying body weight, since the correlation coefficient is not changed if the parameters bone mineral content and ultimate force are corrected for the body weight (Table 1).

It might seem remarkable that in this study of women aged 67–80 no correlation was found between bone mineral content and age. No conclusion regarding the change of bone mineral content with age can, however, be drawn from this cross-sectional study.

The exact mechanism *in vivo* of femoral neck fractures is not known, and we have therefore not been able to reproduce the loading condition leading to femoral neck fractures *in vivo* (Backman 1957, Hirsch & Frankel 1960). Instead we found it more suitable to use a simple loading system which could easily be reproduced. This, however, does not prevent conclusions on the applicability of the theoretical model (see appendix) used, since it describes any loading condition.

It is remarkable that the more carefully analysed parameters, J and M, did not give closer correlations with bone strength than the simple parameter bone mineral content. The reason may be that the bone tissue in the femoral neck is not homogeneous and does not have well-defined mechanical properties, and that the role of the organic tissue has not been taken into account in this study.

The fairly close correlation between bone mineral content and mechanical strength of the femoral neck found in the present study indicates that it is possible to select patients with an increased fracture risk by x-ray spectrophotometry. It would be of interest to check this result with a prospective study of bone mineral content and fracture epidemiology. If a correlation is found, as suspected, then high fracture risk patients should be treated prophylactically. Various methods should be tested to determine their efficiency. The effect of such therapy on the bone mineral content of individual patients can be followed with high precision by the x-ray spectrophotometric method.

APPENDIX

The strength of the femoral neck might not depend on the bone mineral content (mg/cm) only, but also on the distribution of the bone mineral within the cross section of the bone. It is located mainly in the cortical part of the femoral neck where it forms an irregularly shaped pipe. Therefore the femoral neck will be regarded here as a beam subjected to plane bending. Standard formulas for mechanics of materials can then be applied. Two parameters taking the distribution factor into account were used: "mass moment of inertia", J, and a combined parameter, M.

The mass moment of inertia J is calculated from

$$J = \int x^2 dm,$$

where x is the distance of the mass, dm from the neutral axis. J is defined in analogy with the commonly used mechanical parameter moment of inertia

$$I = \int x^2 dA,$$

where x is the distance of the surface, dA, from the neutral axis. The two parameters are related through

$$J = p_A I$$

where p_A is the density, assuming that this density is constant within the bone elements.

The reason for using J instead of I in this study, is that J can be determined experimentally by x-ray spectrophotometry, whereas I cannot easily be de-

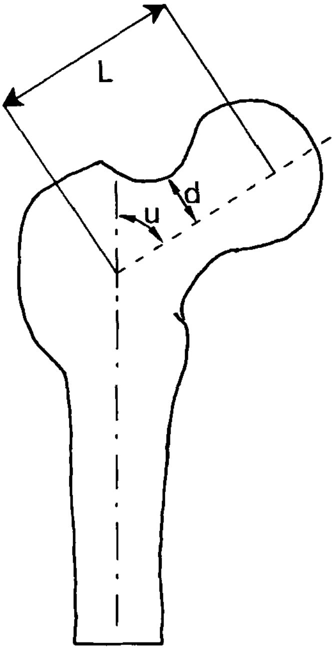

Figure 7. Length (L), and angle (u) of the femoral neck. The distance (d) from the surface to the neutral axis is calculated from the distribution of the bone mineral in the cross section of the bone (see Figure 1).

termined *in vivo*. Just as I is a measure of the bending strength, J is also under the given assumptions.

The parameter M is a combined parameter, calculated in a similar way as J from simple cantilever beam theory. It takes into account both the bending and compressive stress acting in the body. It is calculated as

$$M = \left(\frac{L \cdot d \cdot \cos u}{2 \cdot J} + \frac{\sin u}{m}\right)^{-1}$$

where L is the length of the femoral neck, m the bone mineral content of the femoral neck, u the angle of the femoral neck, and d the distance from the surface to the neutral axis as calculated from the distribution of the bone mineral in the cross section of the bone (Figures 2, 7). The formulas relate to homogeneous and elastic bodies. It was thus assumed that the bone mineral content is proportional to the amount of bone tissue, and that the amount of bone tissue in a cross section is proportional to the area of the cross section.

From x-ray spectrophotometry analysis m, J and M, defined as above, were computed. The angle, u, between the neck and the shaft was obtained from radiographs (Figure 7). The correlations between the ultimate force fracturing the femoral neck and these parameters are presented in Table 1.

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