Bone-mass distribution in the femur

A cadaver study on the relations of structure and strength

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We measured the bone density and volume in the femoral head, cervicotrochanteric, midshaft, and condylar regions by quantitative computed tomography of the femora of 26 elderly cadavers. We also measured the shearing force at fracture of the femora in axial bending; 25 fractures occurred vertically in the neck and only one in the shaft. The bone mass-related measurements, calculated as the product of bone density times volume, increased steadily from the femoral neck down to the condyles. The bone densities of males and females did not differ, whereas the bone volumes were higher in males. Several correlations were found between the ultimate shearing force of the cervical trabecular/cortical bone and cortical and cancellous bone densities in different locations of the femur. The ultimate shearing force was correlated with the bone mass in all the locations.

Given the specific shape of a bone, its mineral content has a clear, although nonlinear, correlation with its strength (Ascenzi and Bell 1972). In a previous study (Alho et al. 1985), we found a good correlation between the density of cancellous bone in the femoral condylar area and the strength of the bone during axial loading until fracture, usually in the femoral neck. In a further computed tomographic analysis, we demonstrated such correlations in various cortical and cancellous regions of the femur (Alho et al. 1988).

We have now determined the distribution of cancellous and cortical bone masses in the femur by quantitative computed tomography and have compared the density and mass with the maximal forces at fracture during axial loading.

Material and methods

We collected femora from 16 male cadavers, median age 75 (56–87) years, and from 10 female cadavers, median age 77(59–88) years. The left femora were used for the study. Between harvesting and the studies, the moist femora were kept in tight plastic packages at -20 °C.

The computed tomograms were made on a GE 8800 equipment (General Electric, Milwaukee, WI) using standard scanning parameters, 120 kV, and 100 mAs. The equipment was calibrated daily. Ten-millimeter-thick CT slices were made from the center of the femoral head, cervicotrochanteric region, mid-diaphysis, and condylar metaphysis (Figure 1). Measurements were made without calibration phantoms because the system was considered stable with a drift of ≤ 4 Hounsfield units (HU) as specified by the manufacturer.

We accepted the HU values as correlated with the bone density, although not in a simple linear fashion. We found a clear dichotomy in the densities of cancellous and cortical bone in various regions. First, we excluded volumes with a density below 50 HU as representing soft-tissue components. In the cervicotrochanteric region, measurements in the parts visually determined as cortical bone gave values exceeding 500 HU, whereas all the values in the areas considered to be cancellous bone had densities well below 500 HU (Table 1). In the diaphysis the mean values in the condylar region were above 500 HU. Therefore, we used 500 HU as the border between cortical and cancellous bone in the regions where this was appropriate. In the femoral head and condylar area, the thinness of the cortical shell made a distinction between cancellous and cortical bone impossible with our measuring technique. In the cervical region the CT slice, due to the scanning direction, included also part of the greater trochanter.

As an approximation of the relative bone masses in a CT slice, we used the product of the mean density and the total volume; the volume was expressed as the slice area times its thickness (1 cm).

After the CT measurements the bones were mounted on an Instron machine (5 ton, Universal Testing Machine, Instron Ltd, High Wycombe, Bucks, UK). An

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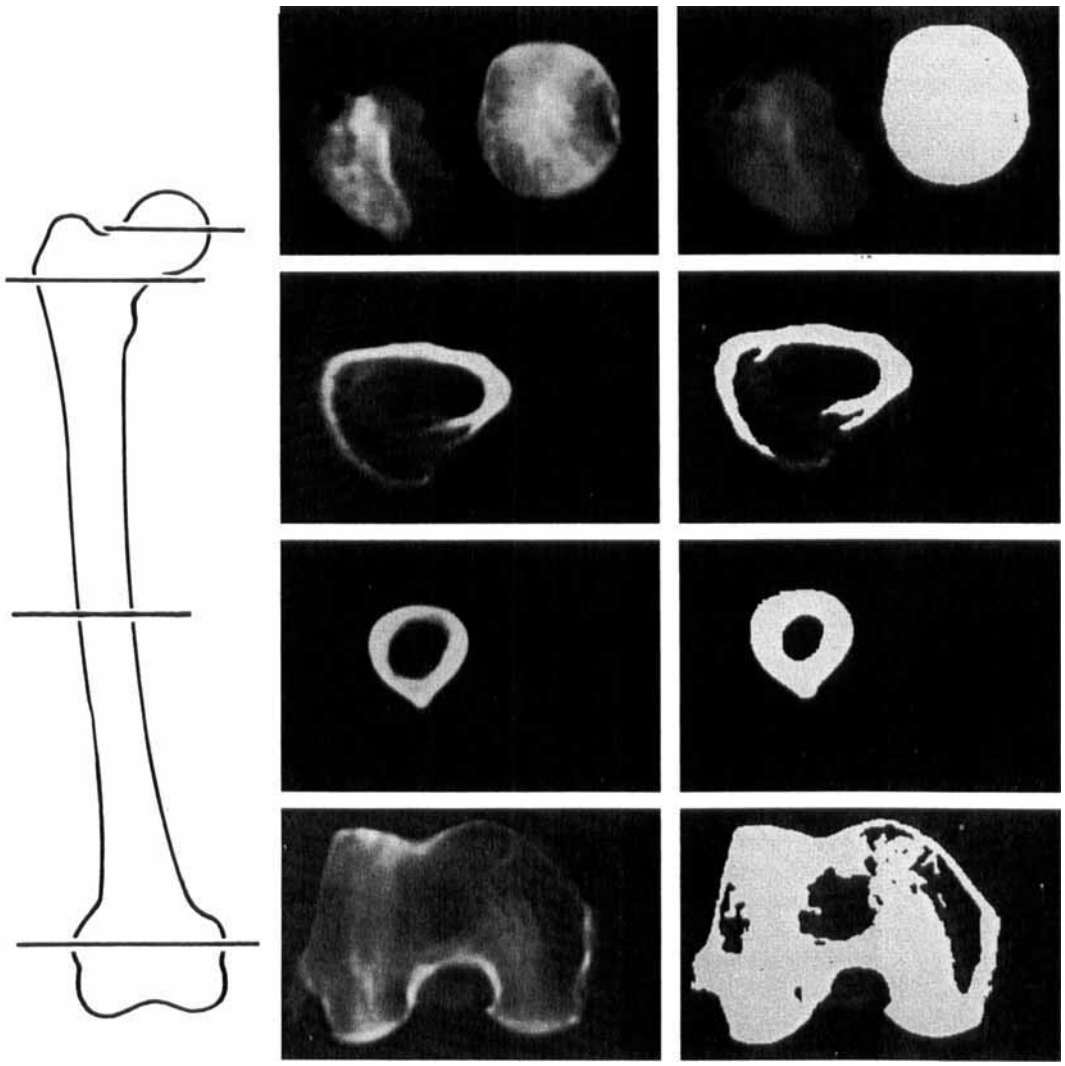

Figure 1. The quantitative computer tomography measurements were performed at the levels of femoral head, cervicotrochanteric area, shaft, and condylar area (drawing on the left). The pairs of computed tomography slices from top to bottom are
Femoral head: Cancellous bone pixels (198–419 HU) are marked on the right.
Cervicotrochanteric area: Cortical bone pixels (739–994 HU) are marked on the right.
Diaphysis: Cortical bone pixels (1,413–1,822 HU) are marked.
Condyles: Cancellous bone pixels (166–365 HU) are marked.

Figures in the parentheses are the average of the specimens with the lowest and highest densities.

Table 1. Bone density-related measurements, volumes, and mass-related measurements in different regions of the femur. The values are mean (SD)

Region	Density (HU)		Volume (cm^3)		Mass (density x volume)	
	Male	Female	Male	Female	Male	Female
Head	310 (64)	285 (57)	19.8 (2.3) [d]	15.4 (1.8)	6140 (1480) [c]	4380 (960)
Neck						
Cancellous bone	180 (66)	145 (40)	13.8 (2.8) [c]	11.4 (1.5)	2370 (740) [c]	1630 (420)
Cortical bone	870 (68)	850 (78)	4.4 (1.9)	3.6 (1.1)	3850 (1770)	3080 (1120)
Sharp	1661 (71)	1610 (89)	4.1 (0.6) [a]	3.6 (0.8)	6900 (1160) [b]	5720 (1080)
Condyles	240 (49)	220 (25)	35.1 (6.4) [b]	23.4 (7.6)	8480 (2030) [d]	5090 (1110)

[a] $P < 0.10$, [b] $P < 0.02$, [c] $P < 0.01$, [d] $P < 0.00.1$

Table 2. The mass-related measurements in computed tomography slices and their correlations (r) to the ultimate shearing force in axial loading of the femur

Region	HU x cm 3 [a]	r [b]
Head	5480 (2210)	0.84
Neck	5640 (2050)	0.79
Cancellous bone	2090 (730)	0.73
Cortical bone	3550 (1600)	0.69
Shaft	6450 (1260)	0.65
Condyles	6890 (2770)	0.75

[a] Mean (SD).
[b] All P values < 0.001.

axial load was applied by placing the condyles on sandpaper on the platform and by applying the crosshead on the femoral head using an interposed sandpaper. The axial load was applied at the speed of 5 mm/min until the bone fractured. The maximal force at fracture was used in the correlation analyses. Twenty-five fractures occurred in the neck and only one in the shaft. In the latter test, the femur started to bow in the shaft. This specimen was included in the analyses. For the calculation of correlations between bone density and ultimate shearing force, and mass and force, respectively, the male and female values were pooled (Table 2).

The Student's two-tailed t-test for unpaired samples was used for the comparison of groups and the least squares method for the regression analyses.

Results

One fourth of the volume of the cervicotrochanteric slice was cortical bone (Table 1). The volume of this cortical bone was as large as the cortical volume of the diaphyseal slice, but its density was only one half of the latter. The density of the condylar cancellous bone was three fourths of the cervical cancellous density.

There was no difference between the male and the female bone densities. The major sex differences were found in the volumes, notably in all the cancellous regions, and in the relative bone masses.

The loads at fracture (the ultimate shearing forces) were 691 ±191 kp (mean ±SD) in the male bones and 515 ± 167 kp in the female bones ($P < 0.05$).

The density of spongy bone of the femoral head correlated with the maximal load at fracture ($r = 0.79$, $P < 0.001$). In the cervicotrochanteric region the cortical density did not correlate with the maximal force at fracture, whereas the density of spongy bone did. The correlation was low ($r = 0.46$, $P < 0.05$) in the shaft, but high ($r = 0.68$, $P < 0.001$) in condylar area.

The correlations were greater between the bone mass and maximal load at fracture in all the studied locations (Table 2). Thus, a correlation ($r = 0.48$, $P < 0.01$) was also found between the maximal load and the diaphyseal cortical mass. A gradual increase in mass was observed from the femoral head to the condylar area, where the mean mass was 26 percent higher than in the upper femur.

Discussion

Several studies have demonstrated correlations between the structural and mechanical properties of various parts of the femur. Leichter et al. (1984) concluded that the shear stresses of the femoral neck at failure were related to the bone density of the greater trochanter. Relations have also been established between the strength and density of bone (Leichter et al. 1984, Esses et al. 1986), and especially trabecular bone (Carter et al. 1987a, Hvid et al. 1987). However, to our knowledge, the conditions in the whole bone, cancellous and cortical bone combined, have not been systematically studied.

It is reasonable to assume that the ultimate shearing force of the femur is related to the loads it is subjected to in everyday life. The mass-related measurements of the transverse computed tomogram slices were higher in the male than in the female bones. The body weights of the cadavers were not available, but we assume that this fact reflects the higher average body weights of males. It is interesting in this sample of elderly bones that the major sex differences were found in the bone volumes. The bone density was also lower in women, reflecting the fact that women in higher age groups are more osteoporotic than men.

The explanation of the fractures of the femoral neck being vertical instead of subcapital and occurring at the neck in 25 of 26 cases was apparently the type of loading; in the cadaver experiments, all the torsional components and the muscle forces were excluded (Husby et al. 1987). Only one specimen, where the femoral shaft started to bow early during the test, fractured at the shaft. In another study, we also had a trochanteric fracture (Alho et al. 1985).

Both density and volume are factors when determining bone strength. To obtain a reasonable approximation, we considered the HU values as density-related measurements and formulated an equation, computed tomographic density times slice volume (cm^3), to describe bone mass. Such mass-related measurements of every femoral region were highly correlated with the force at fracture during axial bending. In the cervical region the share of the cancellous bone was one third, which accords with the earlier observations of Hirsch

and Brodetti (1957), who used strain gauges to measure the load-carrying capacity of the various parts of the femoral neck.

In mechanical terms the bone mass does not describe its strength, the mass values being proportional to the second power of the radii, whereas the polar and axial moments of inertia of tubular structures, which describe their strength better, are proportional to the fourth power of the radii. Also, our mass-related measurements do not exactly describe the relative masses. However, our mass approximations improved the correlation coefficients remarkably. We could even establish a correlation between the cervical cortical bone mass and the ultimate shearing force, in contrast to the density values, which did not correlate with the ultimate shearing force.

Even more interestingly, the bone-mass-related measurements were of the same magnitude — the values of the head and neck were equal and the diaphyseal and condylar values were higher. Of the forces acting in the thigh, the bending moment of body weight decreases upwards: using the body-mass distribution values of Lanz and Wachsmuth (1938), one can calculate that the load of the body at the knee level when standing on both legs is one-third higher than at the hip level. In one leg stance the difference is 14 percent. The increase in our mass-related measurements from the hip to the condyles was of the same magnitude.

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Acknowledgements

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