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Rotational strength of the femoral neck

Computed tomography in cadavers

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The mean bone density of the femur at different levels was determined by means of quantitative computed tomography (QCT) in 50 pairs of normal cadaveric femora and related to the rotational strength of the femoral neck. All the femora fractured vertically and spirally in the neck. The bone-mass-related measures at different levels were calculated from QCT densities and volumes. Cancellous bone was defined with threshold limits ranging from 50–500 Hounsfield units (HU), and attenuation values exceeding 500 HU were assessed as cortical bone. The recorded QCT mass-related measures of cortical and cancellous bone separately and as total bone masses gave significant right/left correlations. Correlations were found between the ultimate torsional strength of the femoral neck and QCT recordings of bone mass at all the femoral levels. The best correlations were demonstrated between the rotational strength of the femoral neck and the total bone-mass-related measures in the femoral shaft and condylar area.

Bone mass of the femur measured by computed tomography may become useful as an index of the mechanical strength of the femoral neck.

Earlier studies have shown good correlation between quantitative computed tomography (QCT) measurements of bone mass of the femur and the ultimate shearing force at fracture in the femoral neck when tested in axial loading (Alho et al. 1988 A, Alho et al. 1988). The purpose of the present study was to investigate the value of computed tomography in assessing the apparent density and mass-related measures at different levels of the femur, related to the ultimate torsional strength of the femoral neck.

Material and methods

Fifty pairs of normal cadaveric femora (74 ± 12 years, weight 50 ± 14 kg, height 163 ± 10 cm [mean ± SD], 32 females, 18 males) were removed and stripped of soft tissue and stored at –18 °C in sealed plastic bags between the experiments. One femur from each pair was used in the mechanical test. Ten-millimeter-thick computed-tomography slices were scanned through the femoral head, neck, trochanter, mid-diaphysis, and condylar area – nine QCT slices per specimen (Figure 1). All the specimens were examined with a GE 8800 scanner (General Electric, Milwaukee, Wisconsin) using single energy (120 Kv, 100 mAs). The QCT assessments were performed without calibration phantoms, because the system is considered to be stable. Ruegsegger et al. (1981) reported a reproducibility of about 0.3 percent when recording QCT on trabecular bone. The positioning of the CT slices were standardized using a localizing image.

The femoral heads were cemented in polyurethane blocks to fit into the testing machine (Instron Machine, 5 ton, Universal Testing Machine, Instron Ltd., High Wycombe, Bucks, England). Prior to cementing, the femoral heads were penetrated with two 2-mm Steinmann pins to avoid slipping on the bone-polyurethane interface. The anterior and posterior surface of the polyurethane blocks were parallel to the femoral diaphysis, and the rotational axis coincided with the center of the femoral neck. The femora were then mounted on the Instron machine, and with the diaphysis fixed horizontally, the femoral heads were rotated at a speed of 0.26r/min (15°/min) until fracture (Figure 2). The load and angular deformation were recorded on an X-Y writer. Maximal torsional moments were calculated for each specimen.

The recordings of density in Hounsfield units (HU)

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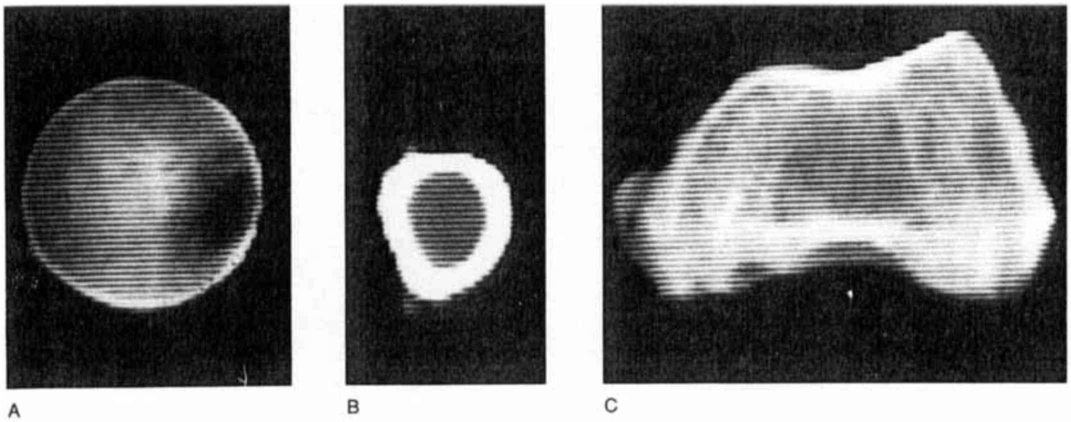

Figure 1. CT slices through the femoral head (A), mid-diaphysis (B), and condyle (C).

and bone volume were performed as described earlier (Alho et al. 1989). Due to the partial volume effect, no distinction was made between cortical and cancellous bone on the CT slices of the femoral head, shaft, and condyles, the lower density limit being 50 HU. In the slices of the femoral neck and trochanteric region, cortical and cancellous bone could be distinguished. The threshold limit 500 HU was based on a visual pilot study. In the femoral neck and trochanteric regions, mean density and volume were also recorded for the combined cortical and cancellous bone. The density-related measure was expressed in HU. Mass-related measure (MRM) was derived from multiplication of mean density times volume.

The following Pearson correlations were made: a) right with left for each CT parameter, b) intercorrelations with all the CT parameters, and c) CT parameters with the rotational strength.

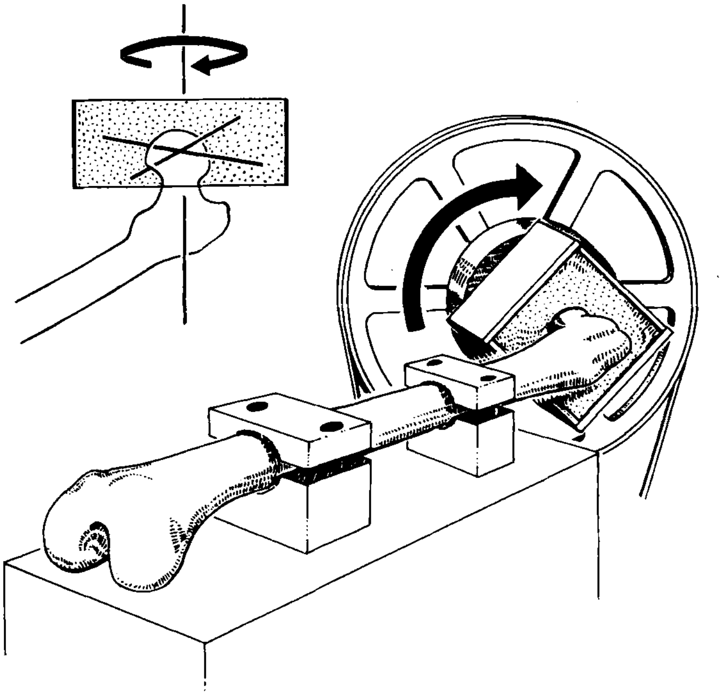

Figure 2. The femoral head was cemented in a polyurethane block and subjected to rotation in an Instron machine.

Results

All the femora fractured vertically and spirally in the neck at an ultimate torsional moment of 74.6 ±28.2 Nm (mean ±SD). The MRM correlated significantly from side to side at all the locations. The right/left correlations were highest in the mid-diaphysis ($r = 0.98$, $P < 0.001$) and lowest in the femoral neck ($r = 0.75$, $P < 0.001$). The bone MRM measures were higher in men than in women (Table 1).

The correlations were highly significant when comparing MRM of the femoral head versus shaft ($r = 0.87$, $P < 0.001$) and condylar area ($r = 0.83$, $P < 0.001$) and comparing the femoral shaft versus the condylar area ($r = 0.87$, $P < 0.001$). Comparing CT slices through bone with similar structure, like the trochanteric and the condylar area, there was a gradual increase in MRM from the proximal to the distal end.

The best correlations were found between the ultimate torsional strength of the femoral neck and the MRM in the femoral head, neck, mid-diaphysis, and femoral condyle (Table 1, Figure 3). In the femoral neck area, we recorded higher correlations between the

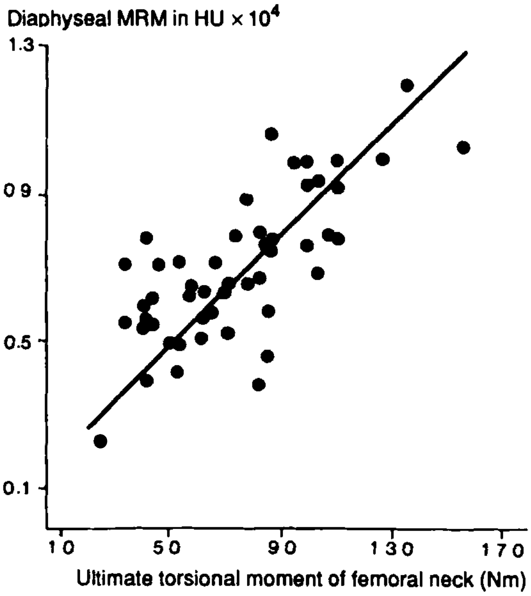

Figure 3. Simple correlation between bone-mass-related measure of mid-diaphysis of the femur and the ultimate torsional moment of the femoral neck ($r = 0.71$).

Table 1. Bone-mass-related measures (MRM) in the femur correlated to ultimate rotational loading of the femoral neck. Mean *SD*

Region		Male (HU)		Female (HU)		Combined F/M		Correlation with ultimate torsional load
Head								
total	H	5889	*1273*	3538	*1177*	4401	*1658*	0.65**
total	P	6655	*1418*	4207	*1257*	5106	*1767*	0.58*
cortical	H	4677	*1031*	3203	*1291*	3596	*1379*	0.57*
spongy	H	2257	*397*	1912	*991*	2007	*875*	0.06
Neck								
total	H	7564	*1240*	5092	*1711*	5751	*1931*	0.41*
cortical	P	2199	*586*	1577	*817*	1801	*796*	0.57*
spongy	P	1610	*446*	1154	*267*	1321	*405*	0.48*
Trochanter								
total		6719	*1518*	4624	*1413*	5382	*1760*	0.57*
cortical		3670	*1365*	2397	*1297*	2850	*1444*	0.52*
spongy		2896	*900*	2254	*703*	2482	*829*	0.26
Diaphysis								
total		8689	*1353*	6047	*1356*	6998	*1855*	0.71**
Condyle								
proximal		7973	*2014*	4609	*1609*	5280	*2389*	0.64**
mid		9524	*2290*	6010	*2277*	7275	*2829*	0.65**
distal		10,560	*2426*	6838	*2176*	8206	*2887*	0.64**

*$P < 0.05$, **$P < 0.001$, H = CT slice in the horizontal plane, P = CT slice perpendicular to the femoral neck.

Table 2. Bone density (HU) correlated with ultimate rotational strength of the femoral neck. Mean *SD*

Region	Male		Female		Male and female		Correlation with rotational strength
Femoral head	346	*57*	289	*75*	309	*74*	0.46*
Femoral neck	428	*78*	379	*104*	397	*98*	0.30
Trochanter	344	*62*	324	*58*	332	*60*	0.32
Mid-diaphysis	1408	*159*	1268	*211*	1319	*204*	0.32
Mid-condyle	264	*64*	217	*58*	234	*64*	0.32

*$P < 0.05$.

ultimate torsional strength and cortical bone MRM than for the cancellous MRM (Table 1).

We also correlated ultimate torsional strength with the bone density for both cortical and spongy bone and mean bone density (Table 2) separately, but did not at any level of the femur achieve as high correlation values as when using the total bone MRM.

The unweighted least squares regression test demonstrated that the bone MRM was a better predictor of the ultimate rotational strength of the femoral neck than age, height, and weight of the patient ($P < 0.01$).

Discussion

Several studies have demonstrated correlations between bone structural or mechanical properties and quantitative computed tomography recordings. Most reports have addressed the value of QCT recordings of trabecular bone (Ruegsegger et al. 1981, Genant and Boyd 1977, Adams et al. 1982), and some have related these data to mechanical properties (Bentzen et al. 1987, Leichter et al. 1984). The present study showed better correlations between the ultimate torsional strength of the femoral neck and the cortical bone MRM than for the spongy bone MRM. This may indicate that cortical bone in the femoral neck contributes more to mechanical strength than the spongy bone, in contrast to the anatomy in the trochanteric region. In osteoporotic women, cancellous bone disappears more readily than cortical bone; perhaps this explains the fact that the cervical/trochanteric fracture ratio decreases with age (Eriksson and Widhe 1988, Falch et al. 1985).

We have previously shown that QCT density recordings, especially in the femoral condyles, correlate with the ultimate bending force in the femoral neck (Husby et al. 1987). Esses et al. (1986) found a highly significant correlation between the force required to create a subcapital femoral neck fracture and the mean QCT density measure in the midcervical region. Our present report shows that when including the total CT slice volume to obtain a bone-mass-related measure the correlation with the mechanical rotational strength of the femoral neck increases. Also, it is possible to determine the relative share of cortical and cancellous bone separately. This accords with the increasing interest in the cortical as well as the spongy bone as the most informative parameter for QCT data when related to bone mechanical properties (Erikson et al. 1988). Our results also indicate that QCT recordings, not only through the femoral neck, but even more so through the mid-diaphysis and condyle, predict the ultimate rotational strength of the femoral neck. The explanation for this is not quite clear. It may be more difficult to obtain standardized projections in the femoral neck area due to different inclination and anteversion angles and the varying size of the specimens. Alho et al. (1988) reported that ultimate bending strength of the femoral neck correlates with QCT recordings of the femur. These findings are confirmed in our present rotational model.

The clinical implications of our findings are not directly obvious, due to the fact that the friction is very low in a normal hip joint, and the acetabulum offers negligible resistance to torsion of the femoral head. However, our model strongly confirms the earlier findings that QCT correlates with bending strength of bone (Alho et al. 1988, Bentzen et al. 1987). It seems important to achieve a thorough understanding of QCT as a mapping instrument of bone properties considering both axial and rotational forces in themselves. Indeed, rotational forces may play a clinical role after a suboptimal reduction/fixation of a femoral neck fracture. From earlier experimental studies, we know that QCT correlates with the bending strength of a femoral neck osteosynthesis (Husby et al. 1987).

The mass-related measure tends to increase as one moves distally in the femur (Alho et al. 1989). Interestingly the MRM increases in the distal direction even within the condyle. This may reflect the fact that the bone density increases rapidly when approaching the subchondral bone (Hvid and Hansen 1985), and addresses the findings of Roux (1881) stating that the dimensions of bone correspond to the physiologic demands.

Our highly significant right/left correlations of QCT recordings indicate the high precision of the method, as stated by others (Ruegsegger et al. 1976, Reich et al. 1976, Peck 1983). Earlier reports have mainly dealt with CT measurements of mean density within a defined volume of bone, thus including both cortical bone and bone marrow (Mazess 1983, Bentzen et al. 1987). Our approach, by defining a lower density threshold limit, may, to some extent, reduce this error.

Using linear regression analysis on our data, we found that the bone-mass related measure of the femoral shift was the best predictor of the ultimate rotational strength of the femoral neck. This is most interesting from a clinical viewpoint, because CT of the mid-diaphysis or condyle is much easier to perform and to standardize than CT through the proximal end of the femur.

A bone-mass-related measure recorded by QCT may become a useful tool for assessment of the femoral-neck bone quality and may even have implications with regard to the choice of treatment for elderly patients.

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