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Original Articles

Cancellous Bone and Mechanical Strength of the Femoral Neck*

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Summary. Twenty pairs of dried macerated femora were submitted to progressive, physiologically oriented loading. The aim of this work was to determine the role of trabecular bone, the importance of the bone mineral density of the femoral shaft, and the importance of the Singh index in the mechanical strength of the femoral neck. By means of an original technique, the influence of both the principal tensile and secondary compressive trabecular groups on the mechanical strength to bending stress has been demonstrated. The artificial destruction of these trabecular groups is responsible for a loss of strength of more than 50% in varus angulation while it has practically no effect in valgus angulation. On the other hand, the mechanical strength of the femoral neck is better correlated with the bone mineral density of the femoral shaft ($r = 0.74$) than with the Singh index ($r = 0.50$) or with age ($r = 0.15$).

The forces exerted on the hip joint during the single-limb-support period of gait have been very well documented by Pauwels [12] and Maquet et al. [10]. It has also recently been shown that the cancellous bone at the upper femoral region presents anisotropic properties [3, 11].

The correspondence between the architecture of the cancellous trabeculae of the proximal femoral extremity and its mechanical stresses has been accepted for a long time [8, 18]. However, to our knowledge, quantitative data are not available to substantiate this relationship.

In the present study, we measured the contribution of the cancellous bone trabeculae from dried macerated femora to their resistance to a progressive loading of physiological orientation. The material was selected in order to study femurs with various caput-collum-diaphysis (CCD) angles ranging from 114° to 144°. Our results were also correlated with the bone mineral density of the corresponding shafts, with the Singh index, and with age.

Material and Methods

The femora of 11 men and nine women aged between 57 and 89 years were selected at autopsy, taking as criterion the identity of the right and left CCD angles. The CCD angles were measured on radiographs of the femora taken in a vertical projection and compensating for the anteversion angle. They varied from 114° to 144°. The bones were immersed in hot water for 2–4 weeks, dried at room temperature, and defatted with chlorothen NU 1.1.1. trichloroethane (Roland, Brussels).

The tests of mechanical strength were performed on the proximal femoral extremities, including the proximal diaphyseal third. The left extremities were taken as controls, while the right ones were emptied of trabecular bone by means of a Volkmann's curette introduced via the medullary cavity. Radiographs (Figs. 1, 2) allowed us to verify the destruction of the trabecular bones, except for those of the femoral head and the principal compressive group (Fig. 2), which were resistant to the curettage because of their greater strength, as already described [7, 11].

Each proximal femoral extremity was progressively loaded by a hydraulically activated metallic cylinder with a concave extremity, pressing on the femoral head at 2 mm/min (Tinius Olsen Testing Machines, Philadelphia, PA, U.S.A.). A specially manufactured metallic base was used to orientate the femoral shafts by 25° to the direction of the loading; this angle corresponds to the 9° of anatomical incline to the vertical of the femur, added to the 16° of mean incline to the vertical of the resultant of the physiological forces applied on the femoral head during walking [10, 12].

The mechanical strength of the femoral necks was evaluated on the basis of their breaking force. The role of cancellous

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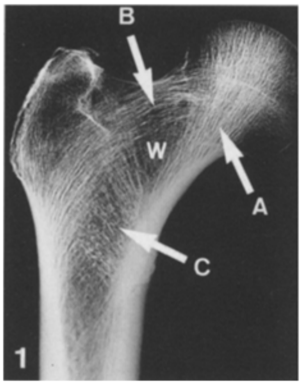

Fig. 1. Radiograph of a human proximal femoral extremity, showing its principal trabecular groups (according to Singh et al. [15]): *A*, principal compressive group; *B*, principal tensile group; *C*, secondary compressive group; *W*, Ward's triangle

Fig. 2. Radiograph of a hollowed femoral extremity. It clearly appears that the cephalic trabecular bone and the principal compressive group were not destroyed by the curettage

bone in the mechanical strength of the femoral neck was evaluated as the ratio of the hollowed femur breaking force to that of the control femur.

The bone mineral density of the control proximal femoral extremities was measured at the level of the proximal diaphysis by dual photon absorptiometry (BMC-Lab. 23: Unité de Rhumatologie, U.C.L., Brussels, Belgium). Their trabecular bone pattern was evaluated on the basis of the Singh index [15].

Results

The femoral neck fractures examined were always symmetrical and usually vertical and transcervical. The two pairs of femora with a CCD angle of more than 140° broke by shearing of the head. The experimental results for men and for women appear in Tables 1 and 2 respectively.

A poor correlation ($r = 0.19$) exists between the CCD angle and the breaking force of the control femora. However, by excluding the only two cases (F9 and H11) where a subcapital fracture occurred, a better correlation is obtained ($r = 0.56$).

On the other hand, in both sexes, a correlation was seen between the ratio of the breaking forces and the CCD angle. This relation is shown in Fig. 3; the ratio of the breaking forces increases linearly with the neck-shaft angle ($r = 0.91$). Therefore, the more the angle is open, the less is the contribution of the cervicotrochanteric trabeculae to the mechanical strength of the femoral neck. However, the subjects with a very open CCD angle and subcapital fractures are again exceptions.

Finally, the mechanical strength of the control femora seemed better correlated with the bone min-

Table 1. Quantitative parameters of the femora in 11 men

Patient	Age	CCDA	LBF (kg)	LBMD[a]	RBF (kg)	Singh index
1.	71	114°	645	0.937	365	3
2.	75	116°	962	1.339	388	5
3.	74	118°	1160	1.415	753	4–5
4.	57	120°	1772	1.505	1349	6
5.	71	122°	1241	1.625	822	5
6.	72	124°	1208	1.597	850	4–5
7.	70	126°	768	0.978	635	4
8.	72	126°	1645	1.460	1205	4
9.	63	132°	1992	1.631	1762	4–5
10.	78	134°	1843	1.428	1806	4–5
11.	77	142°	722	1.259	369	3–4

CCDA, Neck-shaft (caput collum diaphysis) angle; LBF, left (control) femur breaking force; LBMD, left (control) femur bone mineral density; RBF, right (hollowed) femur breaking force

[a] BMD, Mean bone mineral density = $_{g}BA_{(N)}/cm^2$

Table 2. Quantitative parameters of the femora in nine women

Patient	Age	CCDA	LBF (kg)	LBMD[a]	RBF (kg)	Singh index
1.	65	116°	633	1.153	342	5
2.	68	118°	520	0.972	297	3
3.	73	122°	1093	1.340	642	3
4.	70	124°	1203	1.306	854	3–4
5.	71	126°	1335	1.301	1100	4–5
6.	71	128°	920	0.962	775	4
7.	64	128°	802	1.244	715	3
8.	72	130°	1090	1.260	990	3
9.	69	144°	928	1.105	401	3–4

CCDA, Neck-shaft (caput collum diaphysis) angle; LBF, left (control) femur breaking force; LBMD, left (control) femur bone mineral density; RBF, right (hollowed) femur breaking force

[a] BMD, Mean bone mineral density = $_{g}BA_{(N)}/cm^2$

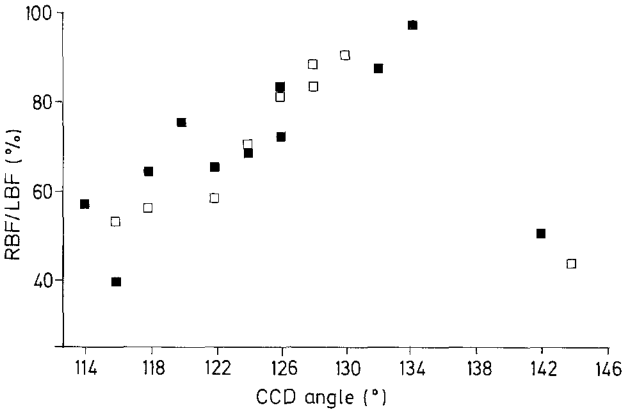

Fig. 3. Ratio of the breaking forces *(RBF/LBF)*, as a function of the neck-shaft angle *(CCD angle)*; $r = 0.91$; ■ men; □ women

eral density of the proximal shaft ($r = 0.74$) than with the Singh index ($r = 0.50$) or with age ($r = 0.15$).

Discussion

Fractures produced after physiological loading of the proximal femoral extremities, i.e., a vertical and transcervical line of break, were also systematically observed by Leichter et al. [9] on 32 cadaveric femora. Thus, the two pairs of femora which broke by shearing of the head seem to differ from the norm. We have described elsewhere [5] this type of femur, which, in addition to an extremely open CCD angle, presents a very narrow shaft and an absence of osteoporosis on microradiographic analysis.

The most important correlation is that observed between the CCD angle and the ratio of the right and left breaking forces. In our opinion, the removed trabecular bone, i.e., mainly the principal tensile and the secondary compressive groups, may prove to be of prime importance in the mechanical resistance to bending stress; indeed, the greater the varus angulation and the greater the bending component of the joint load [2], the greater the role which both these trabecular groups play in the mechanical strength of the femoral neck. Therefore, the cancellous bone of the upper femoral extremity should be regarded as an anisotropic material [3, 11] with a quite specific contribution to the strength of the femoral neck, and not as having undefined mechanical properties [4].

The bone mineral density of the femoral shaft, considered by Bohr and Schaadt [1] to be better factor in femoral neck fracture risk in vivo, seems also to be an important factor in the mechanical strength of the femoral neck in vitro, independent of the CCD angle ($r = 0.74$). Other in vitro experiments have shown a similar correlation between the mechanical strength of the femoral neck and its bone mineral content or density, measured by various techniques [4, 9, 14]. However, Leichter et al. [9] point out that with increasing age, the compressive strength of the femoral neck decreases more rapidly than its bone mineral density, and that the strength of bone tissue may also be due to some other factors which are age dependent. We believe that osteoporosis can explain this phenomenon, as it can specifically change the mechanical properties of the load-bearing trabecular bone [16], and that the anisotropy of the cancellous bone cannot be assessed by measurements of bone mineral content.

The poor correlation ($r = 0.50$) between the Singh index and the breaking force of the femoral necks agrees with the results of Leichter et al. [9] ($r = 0.49$). The limitation of this index for estimation of the strength of the neck in vitro and of its fracture risk in vivo [13] may be due to the fact that the progressive loss of the different trabecular groups affects the strength of the neck according to its neck-shaft angle.

Finally, the fact that no correlation is found between the subjects' age and the mechanical strength of the femoral necks agrees with the results of Dalén et al. [4]; it may be due to the narrow age range.

In conclusion, the cancellous bone of the proximal femoral extremity should be regarded as an important factor contributing to the mechanical strength of the femoral neck, due not only to its bone mineral content, but also to the particular architecture of its trabecular groups. Our experiment has clearly shown the role of the principal tensile and secondary compressive groups in the mechanical resistance to bending stress. Indeed, the artificial destruction of both these trabecular groups is responsible for a loss of more than 50% of the neck strength in the coxa vara, while it has no effects in the coxa valga. These facts, combined with the relative fragility of the control proximal femoral extremities in varus position, lead us to ask whether senile or postmenopausal osteoporosis at the level of the cancellous bone of the proximal femoral extremity may not be more detrimental in cases of coxa vara. Indeed, it is widely recognized [6, 15, 17] that osteoporosis, in the same manner as the mechanical destruction by curettage in our experiment, affects the principal tensile and secondary compressive groups rather than the principal compressive group, which is relatively well preserved.

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