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Subchondral bone strength in arthrosis

Cadaver studies of tibial condyles

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We measured the axial penetration strength of subchondral cancellous bone in a close, regular pattern at the tibial resection surface of five valgus and seven varus human, cadaveric knees. The strength patterns obtained were illustrated by pseudo-three-dimensional reconstructions of strength values as a function of the location on the resection surface. The varus knees had high strength values towards the medial margin of the medial condyle. Three qualitatively different strength patterns were distinguished in the valgus knees: two knees showed a near normal strength distribution with higher peak values medially; two knees with centrolateral bony attrition had high bone strength values at the center of the lateral condyle; and one knee with moderate posterolateral bony attrition showed a high strength area at the posterolateral aspect of the lateral condyle. In both types of malalignment, there was a decrease of bone strength with the depth from the resection surface.

Strength measurements on cancellous bone of the arthritic knee reported earlier (Behrens et al. 1974, Lereim et al. 1974) gave only a vague idea of strength distribution as a function of alignment; two of the knees from the clinical series reported by Behrens et al. (1974) included measurements from both tibial condyles showing higher medial strength in a varus knee and higher lateral strength in a valgus knee; alignment was not reported by Lereim et al. (1974), but a general preponderance of higher medial hardness values was found.

Our aim was to provide a detailed description of the distribution of axial strength of tibial subchondral bone from a series of malaligned knees collected from routine autopsies.

Material and methods

Knee joints including approximately 15 cm of distal femur and 15 cm of proximal tibia were removed at autopsy and immediately deep frozen to below −21°C, a procedure known to retain the mechanical properties of bone (Sedlin & Hirsch 1966). Clinical information was collected from the patients' files and the autopsy reports (Table 1). The level of physical activity prior to death was graded 0 to 3 from non-ambulatory to an almost normal level of activity.

Femoro-tibial alignment was measured directly on the specimens under simulated weight-bearing. Varus-angles were given a negative sign. Arthrosis was graded according to Ahlbäck (1968), as described by Egund et al. (1980): medial or lateral subluxation was recorded.

Prior to mechanical testing the joints were thawed for 18–24 h at room temperature. Soft tissues were removed. The joint surfaces were resected with a band saw close below the subchondral bone plate; in the knees with substantial attrition (knees nos. 3, 4 and 6) resection was through the compact sclerotic bone to mimic the tibial bone resection in total knee replacement. An additional parallel cut with the saw produced epiphyseal slices approximately 2 cm thick.

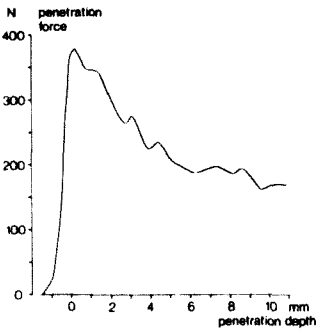
The mechanical tests were performed as penetration tests with equipment referred to as an osteopenetrometer and primarily designed to obtain *in vivo* cancellous bone strength measurements during total knee replacement (Hvid et al. 1984, Hvid 1985). A pointed needle with a diameter of 2.5 mm at the base of the measuring profile and the needle shaft milled to 2.3 mm to eliminate friction was used. Measurements were recorded as force-depth diagrams from which penetration strength values from five consecutive 2 mm depth intervals were derived (Figure 1), by averaging the force across the interval and dividing by the projected cross-sectional area of the needle. The speed of penetration was kept constant at 1 mm s^{-1}. The penetration strength reported here relates closely to strength parameters derived from compression tests on machined bone specimens, e.g. the ultimate strength is roughly half the penetration strength value.

Table 1. Characteristics of donors. Stage slightly modified from Ahlbäck (1968)

Knee No.	Cause of death	Age (years)	Sex	BW (kg)	Phys. act.	Side	Knee-angle (degrees)	Stage (M/L/P)	Comment
1	A	92	F	39	2	R	29	1/3/3	ACL gone, anterolateral instability, marginal posterolateral attrition
2	B	76	F	78	1	R	15	1/2/1	
3	C	84	F	43	1	L	22	3/4+/3	RA > 20 years; no steroid therapy, centrolateral attrition
4	D	86	F	62	1	R	30	1/4/3	ROM 20/100, centrolateral attrition
5	B	77	F	63	1	L	30	0/1/3	Primary genu valgum
6	B	85	M	56	1	R	−20	4+/1/3	
7	B	78	M	63	1	L	0	1/1/1	Medial meniscectomy 40 years prior to death
8	B	85	M	56	1	L	−1	3/1/3	
9	B	92	F	40	1	R	−5	3/1/2	ROM 10/90, pyrophosphate deposits
10	A	90	M	51	3	R	−10	3/1/2	ROM 15/90
11	C	69	F	75	3	R	0	2/0/2	ROM 20/90
12	C	71	F	60	2	L	−5	2/1/2	Steroid treatment for 2 months

Knees nos. 6 and 8 were from the same patient. Cause of death: A pneumonia, B heart disease, C cancer, D gastric bleeding.

The measuring cylinder was mounted firmly in a heavy metal frame (Figure 2). The epiphyseal specimens were measured in a regular quadratic pattern with 5 mm between measurements (Figure 2); thus, 96–127 measurements were obtained from each specimen. The specimens were kept in physiologic saline prior to testing. The testing procedure, usually lasting about 1 h, was performed at ambient temperature and humidity; the specimen was soaked with saline every 5 min to avoid drying. Destruction of



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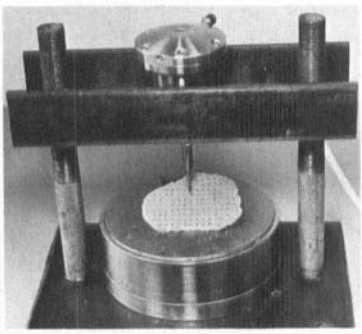

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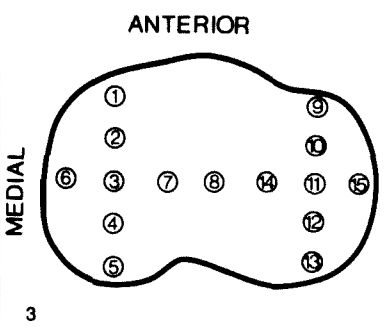

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Figure 1. A penetration test curve. Zero depth is defined as a point 1.5 mm deep to the first deflection of the curve, since at this point the full measuring profile has penetrated the resection surface. The following five 2-mm deep intervals were designated Levels 1–5.

Figure 2. The osteopenetrometer with a section of a tibial epiphyseal specimen after measurements have been completed.

Figure 3. Regions of interest employed to study medial-lateral and proximal-distal strength distribution. Fixed points were the central condylar points and the marginal measurements; additional points were found by bisecting distances between the first points.

Table 2. Variation of bone strength with depth in the varus knees. ROI = Region of interest (Figure 3). MBS-1 = mean bone strength Level 1 (Figure 1)

ROI	MBS-1 (MPa)	Level 1–3			Level 3–5			Level 1–5
		Mean difference (MPa)	5	P	Mean difference (MPa)	t	P	(Per Cent)
1	39.8	3.8	0.84	0.435	−2.1	−0.24	0.818	4
2	13.1	−0.9	−0.49	0.644	−1.0	−0.37	0.726	−14
3	24.9	−5.9	−2.29	0.062	−1.2	−0.49	0.638	−29
4	34.4	−11.8	−3.39	0.015	−3.5	−1.64	0.153	−45
5	34.0	−7.6	−1.94	0.101	−4.6	−1.54	0.175	−36
6	24.3	4.8	1.62	0.156	4.8	0.84	0.432	40
7	10.1	−1.5	−1.05	0.332	−2.2	−1.04	0.340	−37
8	3.3	0.4	0.48	0.652	0.2	0.34	0.744	18
9	9.2	−3.4	−1.16	0.291	0.9	0.56	0.596	−27
10	7.4	−0.7	−0.30	0.771	0.1	0.08	0.941	− 8
11	8.4	−2.8	−3.88	0.008	−0.5	−1.35	0.227	−39
12	10.5	−3.5	−2.06	0.085	−1.3	−1.59	0.162	−46
13	15.1	−5.1	−2.05	0.086	−0.5	0.40	0.706	−37
14	9.6	0.8	0.31	0.767	−1.4	−1.01	0.353	− 6
15	7.3	−0.1	0.04	0.972	1.3	0.94	0.386	16

the trabecular structure adjacent to the penetration track was very limited, regardless of the local density (Sneppen et al. 1981).

The test curves were evaluated off-line after transmission to a microcomputer. The operator defined the start of the curve; the program ignored the following 1.5-mm depth interval representing increasing contact with the measuring profile, and computed the penetration strength for the following five 2-mm intervals (Figure 1). The data from each specimen were then structured in five two-dimensional rectangular matrices (corresponding to the five depth levels) where the location in the matrix corresponded to the location at the resection surface (the undefined "corner" values being filled in with zeroes), and the data consisted of the bone strength values. The data were then smoothed, utilizing an algorithm described by Shepard (1968), smoothing parameters being chosen arbitrarily to give minimal smoothing with less than 5 per cent reduction of peak bone strength values. A pseudo-three-dimensional diagram of the strength profile as a function of surface location was plotted using a graphic program package (DISSPLA), available at the regional university computer center (RECAU). To facilitate further evaluation, a number of regions of interest were defined (Figure 3); these regions were applied directly to the non-smoothed matrices to identify the bone strength at the region, using simple linear interpolation when necessary. The mean value from regions 1–7 was referred to as medial and from regions 9–15 as lateral condylar strength.

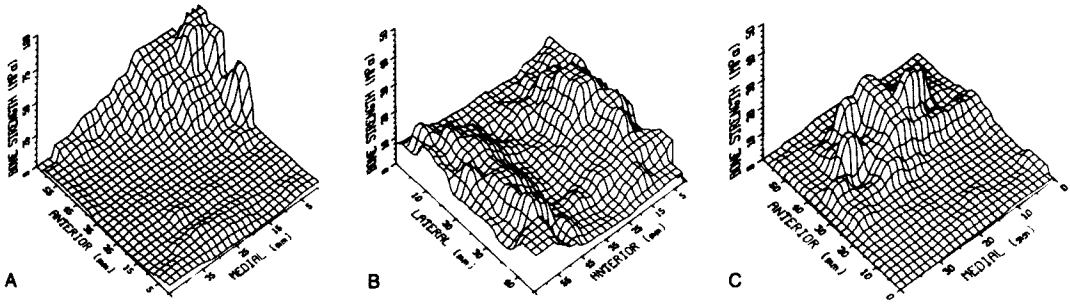

Figure 4. Examples of strength profiles of valgus knees. The patterns were reconstructed to give the impression of looking at the tibial resection surface of a right knee from a point above, in front and medial or lateral, as convenient, to the knee. Note that the values on the Z-axis (bone strength) differ. A Knee no. 1. B Knee no. 2. C Knee no. 3.

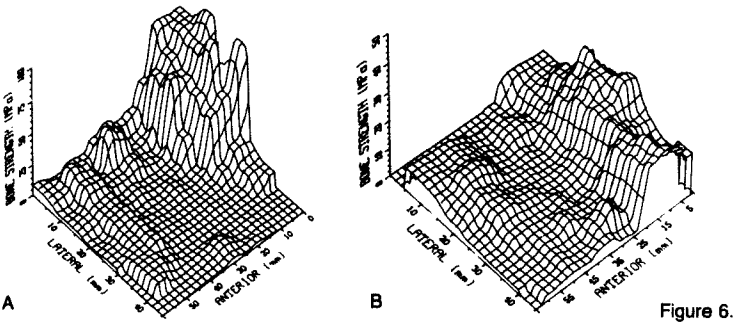

Figure 5. Examples of strength profiles of varus knees. A Knee no. 10. B Knee no. 12.

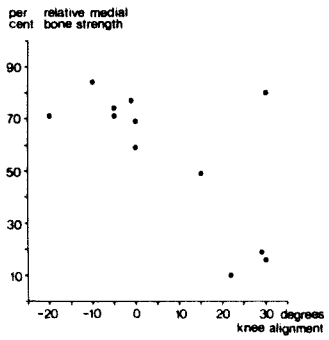

Figure 6.

Figure 6. Dependence of medial-lateral bone strength distribution on malalignment. Relative medial strength was calculated as medial condylar strength in per cent of medial + lateral condylar strength.

Results

Examples of the strength profiles obtained in the valgus knees are shown in Figure 4. The small sample of valgus knees was heterogeneous with respect to the general features of the profiles. Three different patterns could be distinguished: one in which there was a posterolateral marginal high strength area and very low medial strength (knee no. 1); one in which there was a centrolateral high strength area and low medial strength (knees nos. 3 and 4); and one in which the medial condylar strength predominated (knees nos. 2 and 5). The variation of bone strength with the depth from the resection surface also varied considerably; except for knee no. 1 which showed very little change with depth, there was a general tendency toward considerable reduction of bone strength with depth at the stronger condyle (40–60 per cent total reduction of central condylar values relative to level 1; the reduction was more pronounced between levels 1 and 3 than between levels 3 and 5), while the reduction was less pronounced at the weaker condyle (0–25 per cent).

The varus knees showed more homogeneous general strength profile features (Figure 5) with predominant medial strength in all knees and with relatively high values being obtained from the medial margin of the medial condyle, more so in severe varus. In the knee with medial subluxation of the femur on the tibia (knee no. 6), the relatively high strength area at the lateral condyle was more prominent toward the intercondylar area in contrast to the general trend where a more posterior location was noticed. The variation of bone strength with depth was quite uniform in the varus knees (Table 2); there was a marked reduction of bone strength with depth at the central aspects of the condyles, while at the high strength area at the medial margin of the medial condyle, no reduction of strength with depth was noted.

There was a significant influence of the type and degree of malalignment on the relative distribution of bone strength values between the medial and the lateral condyles (Figure 6). The overall average bone strength (regions 1 to 15) also depended on alignment; the varus knees were generally strong, and the valgus knees were weak ($r = -0.69$, $t = 3.02$, $P = 0.013$). There was no correlation between age ($r = -0.01$) or between body weight and average bone strength ($r = 0.15$). Furthermore, there was no correlation between either the physical activity or the Ahlbäck-stage and average bone strength (Spearman rank correlation, $r_s = 0.37$ and $r_s = -0.06$, respectively).

Discussion

The bone strength patterns found are probably a reflection of the overall load distribution at the malaligned knee (Wolff 1892). Gait studies, although dependent on a number of assumptions, some of which are subject to discussion (Maquet 1984), have shown a normal preponderance of medial compartmental load (Har-

rington 1983), which is augmented by varus malalignment, but not always reversed by valgus malalignment (Johnson et al. 1980, Harrington 1893). A compensatory gait pattern in some patients with valgus malalignment, reversing the more lateral location of the center of weightbearing predicted by static analysis, was implied (Johnson et al. 1980).

The pattern of lateral attrition usually seen with severe degeneration of the lateral compartment is central condylar scooping (Ahlbäck 1968), which we found in knees nos. 3 and 4 (Figure 4-C and Figure 6-A). The series included an example of severe valgus malalignment with marginal posterolateral attrition. This type of attrition, the result of chronic anterolateal instability, is apparently rare and was not described by Ahlbäck.

The rapid reduction of bone strength with depth at the stronger condyle supports the concept that the tibial resection in total knee replacement should be as conservative as possible. The low bone strength values found at the convex side of the deformity, notably in some of the valgus knees, suggest that operative overcorrection of malalignment might create a situation where the load-bearing capacity of the weakened condyle could easily be exceeded.

In view of the highly abnormal topographical distribution of bone strength as a consequence of abnormal weightbearing at the knee, it is interesting to note that the remodelling activity in the subchondral bone in arthrosis is low (Havdrup et al. 1976, Christensen et al. 1982). The finding of large quantities of woven bone at the loaded condyle (Christensen et al. 1982), however, is suggestive of an early "productive" phase in the development of arthrosis, and possibly related to the finding of high strength values at the margin of the loaded condyle in varus malalignment and some cases of valgus malalignment.

Acknowledgements

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