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COMPRESSIVE STRENGTH OF TIBIAL CANCELLOUS BONE

Instron® and Osteopenetrometer Measurements in an Autopsy Material

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The topographic variation of proximal tibial cancellous bone strength was investigated in 12 knees from routine autopsies. Samples from eight knees were tested to compressive failure in an Instron® material testing machine, and four knees were tested with the osteopenetrometer, an instrument developed for intraoperative measurement of bone strength. Ultimate stress, elastic modulus and energy absorption of the bone were calculated from the Instron-curves. Mechanical properties varied considerably from knee to knee, but the topographic patterns were remarkably constant. The medial condyle showed the highest strength, the intercondylar area the lowest. On the medial side the bone was strongest at the front, while on the lateral side the reverse was true. The two horizontal levels tested did not differ significantly. The osteopenetrometer measurements closely modelled the pattern of ultimate stress.

Key words: biomechanics; cancellous bone strength; knee.

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Failure of non-hinged total knee prostheses because of component loosening or trabelular bone collapse most often occurs at the tibial component of the prosthesis. This has been shown in clinical studies (Insall et al. 1976, Ducheyne et al. 1978, Insall et al. 1979, Cameron & McNeice 1981), and in an experimental investigation all failures took place on the tibial side (Nogi et al. 1976). Total coverage of the tibial resection surface including the thin cortical shell is not a realistic possibility with most surface-replacing prostheses in clinical use. Furthermore, stress analysis under conditions of realistically distributed load has shown that variation of the size of the tibial component does not significantly affect bone stress levels when the prosthetic component is all-plastic as opposed to metal-backed components (Murase et al. 1983). Thus, it is apparent that the strength of the cancellous bone of the proximal tibial epiphysis is crucial to the prognosis after total knee replacement of the non-hinged design.

Data on material properties of the proximal tibial epiphysis are relatively sparse. Behrens et al. (1974) and Lindahl (1976) used compression-tests of machined specimens. Bargren et al. (1978) examined tibial resection-surfaces *in situ* by means of an indentation-test. Lereim et al. (1974) tested the hardness of trabecular bone at the knee, a property not necessarily equivalent to the solidity of the structure (Frost 1973). Yuzuki (1977) studied the resistance of the joint surfaces and underlying bone to penetration. None of these methods in the forms conducted are applicable to intraoperative *in vivo* measurements.

The intention of the present study was to contribute to the knowledge on the topographical distribution of trabecular bone strength at the proximal tibial epiphysis employing conventional Instron® testing and to compare the results of such testing with those obtained with the osteopenetrometer, an instrument suitable for intraoperative use developed at our institution (Sneppen et al. 1981).

MATERIAL AND METHODS

Knees were obtained within 24 h post mortem and refrigerated to below −18°C. Machining of the frozen specimens took place on the same day as the tests were performed. Eight knees from routine autopsies (four female, four male, age range 19–65 years, mean age 47 years), all with normal knee alignment and with no known bone disease, were prepared for Instron testing as follows. The soft tissues and femur were removed and the tibial joint surfaces were resected immediately below the cartilage using a power saw, leaving a tibial epiphyseal resection surface at a right angle to the tibial axis. To ensure reproducible measuring sites, the outline of the tibial resection surface was copied on to paper. Two parallel lines were drawn tangentially to the lateral and medial margins of the tibia. The widths of the tibial condyles were marked and three sagittal lines constructed corresponding to the midlines of the condyles and the intercondylar area. The condylar lines were divided into four equal parts, thus defining three measuring points on each condyle. Intercondylar measuring points were chosen where lines connecting corresponding condylar points transected the sagittal intercondylar line (Figure 1). These nine points were then transferred to the tibial resection surface. An 8 mm trephine was centred on the points at right angles to the surface to remove nine cylindrical specimens from each tibia. The specimens were further divided in proximal and distal cylinders, each approximately 8 mm long. The length of each cylinder was recorded for calculation of relative strain. The deformation rate was 2 mm/min. Tracings of force were recorded at constant paper speed, permitting calculation of strain. From the curves, ultimate stress (ultimate force/cross-sectional area of test cylinder, MPa), elastic modulus (MPa) and energy absorption at failure (Jm^{-3}) were calculated (Figure 2). Sometimes the curves showed relative plateaus before the maximal force was reached (Lindahl type I-curve (Lindahl 1976)). The first plateau was then recorded as the ultimate force of the specimen. The modulus was calculated from the slope of the tangent at 67% ultimate force.

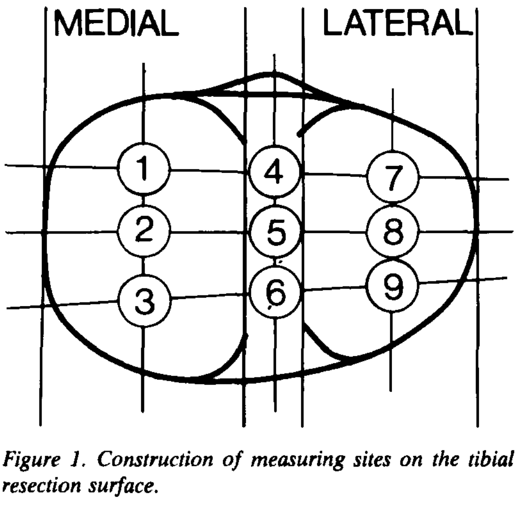


Figure 1. Construction of measuring sites on the tibial resection surface.

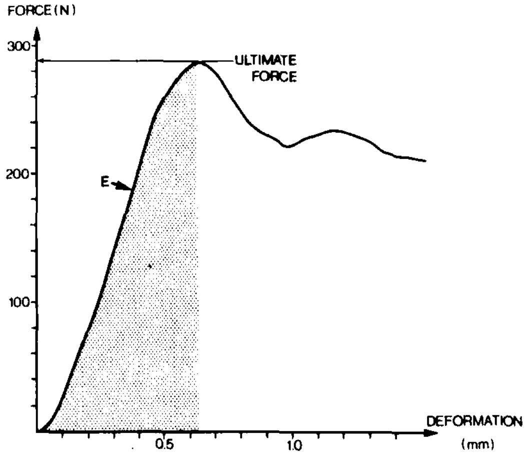


Figure 2. Copy of an Instron®-test curve with the X-axis converted to show deformation. The shaded area is a measure of the energy stored in the bone at ultimate strain. "E" denotes the point at which the tangent for calculation of the elastic modulus is constructed.

Four knee preparations (one female, three male, age range 37–59 years, mean age 46 years) were tested with the osteopenetrometer. This instrument has been described earlier (Sneppen et al. 1981). In essence it consists of a 2.5 m pointed needle that can be advanced by standard power tools through a mechanical coupling. For these measurements the penetrometer was firmly mounted in a heavy metal stand with the needle right over the measuring site of the specimen (Figure 3). The needle was then advanced, penetrating the trabecular bone down to 9 mm below the proximal resection surface. Transducers transmit the penetration distance and penetration force to an X-Y recorder. Figure 4 shows a typical penetrator curve. Penetration work for any level below the resection surface can be estimated by measuring the area below the appropriate curve seg-

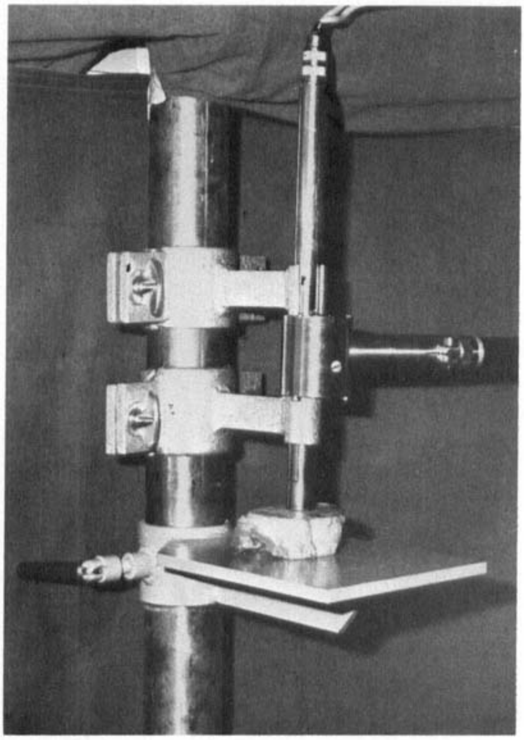


Figure 3. The osteopenetrometer ready for measurement.

ment. For the purpose of the present comparison, levels 2–3 mm and 8–9 mm below the resection surface were chosen.

The specimens were machined by horizontal section beneath the cartilage and an additional parallel cut 2 cm distal to the first cut. Multiple measurements were made in a random pattern with at least 5 mm between each measuring site. Nine circular areas with a diameter of 8 mm were then outlined on the resection surface in the same manner as described above. When more than half of a defect left by the penetrator was inscribed by the circle, this measurement was included in that measuring area. Most often, two to three penetrometer measurements were included in a measuring area; the mean of these values was used as the penetration work characteristic of that area.

RESULTS

Table 1 shows the results from the various measuring sites. There is a strong correlation between ultimate stress and energy absorption ($r = 0.74$, $N = 131$, $P < 0.001$), somewhat weaker between ultimate stress and elastic modulus ($r = 0.59$, $N = 131$, $P < 0.001$), and insignificant between elastic modulus and energy absorption ($r = 0.13$, $N = 131$, N.S.).

Four-way analysis of variance of these data (variables: knee, depth, frontal position, sagittal position) showed that there was no statistically significant interaction between any sets of three variables taken together. Two-way analysis of variance between any pair of variables was therefore permissible (The Bartlett test was performed in a limited number of instances and showed no significant inhomogeneity of variances). It is apparent from Figure 6 that there was one knee with an incomplete sample of data in the penetrometer-tested group. The missing measurements (one in the proximal test-level and one in the distal test-level) were reconstructed from the other data so that all four knees could be included in the two-way analysis of variance. Compared to the four-way analysis, where the missing data were not pre-estimated, the same result emerged.

Several knees in the Instron-tested group had incomplete samples from the distal test level. Only the four knees with complete samples were considered when analysis involved the distal test level.

Ultimate stress showed significant individual variations between the eight knees tested (proximal test level: $F_{7,48} = 3.21$, $P < 0.01$). When knees were tested against location of samples, no significant interaction was found; this may be interpreted that the change of ultimate stress *pat-*

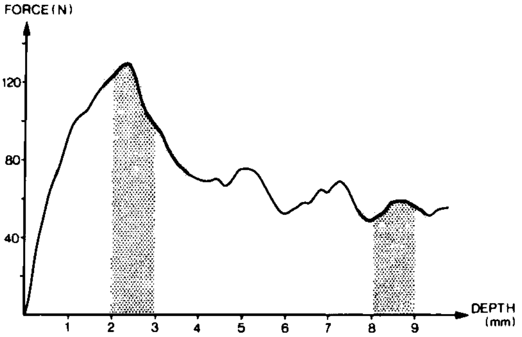


Figure 4. Copy of a penetrometer-test curve. The shaded areas show the penetration work at the test levels.

Table 1. Distribution of physical properties of cancellous bone of the proximal tibial epiphysis. A: proximal level. B: distal level. Numbered measuring sites refer to Figure 1. Values given are mean (SEM)

	Measuring site	Number	Ultimate stress (MPa)	Elastic modulus (MPa)	Energy absorb. ($\times 10^5$ Jm^{-3})	Number	Penetration work (N mm)
A	1	8	7.8 (1.6)	157 (42)	3.0 (0.8)	4	58 (10)
	2	8	5.1 (0.7)	171 (74)	1.9 (0.5)	4	32 (11)
	3	8	5.5 (0.7)	117 (21)	2.1 (0.3)	4	30 (7)
	4	8	1.7 (0.6)	64 (23)	0.7 (0.4)	4	22 (4)
	5	8	1.2 (0.4)	27 (8)	0.4 (0.2)	4	13 (2)
	6	8	3.4 (0.9)	42 (4)	1.8 (0.7)	4	18 (4)
	7	8	2.8 (0.6)	63 (9)	1.1 (0.3)	3	29 (3)
	8	8	3.2 (0.4)	73 (12)	1.2 (0.3)	4	20 (2)
	9	8	6.3 (0.7)	114 (18)	2.3 (0.3)	4	43 (3)
B	1	6	7.3 (1.8)	246 (132)	2.2 (0.6)	4	64 (17)
	2	8	5.7 (1.1	181 (84)	2.2 (0.6)	4	38 (12)
	3	5	7.7 (1.1)	345 (221)	2.3 (0.5)	4	38 (11)
	4	7	1.5 (0.8)	32 (14)	0.6 (0.4)	4	15 (3)
	5	7	0.6 (0.2)	14 (5)	0.3 (0.1)	4	16 (4)
	6	6	3.8 (0.8)	87 (13)	1.2 (0.3)	4	32 (12)
	7	7	2.4 (0.6)	56 (13)	1.0 (0.4)	3	15 (6)
	8	8	2.8 (0.4)	71 (12)	0.9 (0.2)	4	30 (9)
	9	5	6.7 (0.5)	110 (9)	2.7 (0.4)	4	50 (8)

tern between knees was insignificant. At the proximal level there was a highly significant variation of ultimate stress in the frontal plane ($F_{2,63}$ = 18.77, $P < 0.01$), and also the sagittal plane showed significant variation ($F_{2,63}$ = 4.26, $P < 0.05$). Furthermore, interaction was significant ($F_{4,63}$ = 3.33, $P < 0.05$), indicating that the relationship between the three levels of frontal measurements shifts with the sagittal level (Figure 5). At the distal level the same pattern was found. There was no significant difference between the two horizontal levels tested.

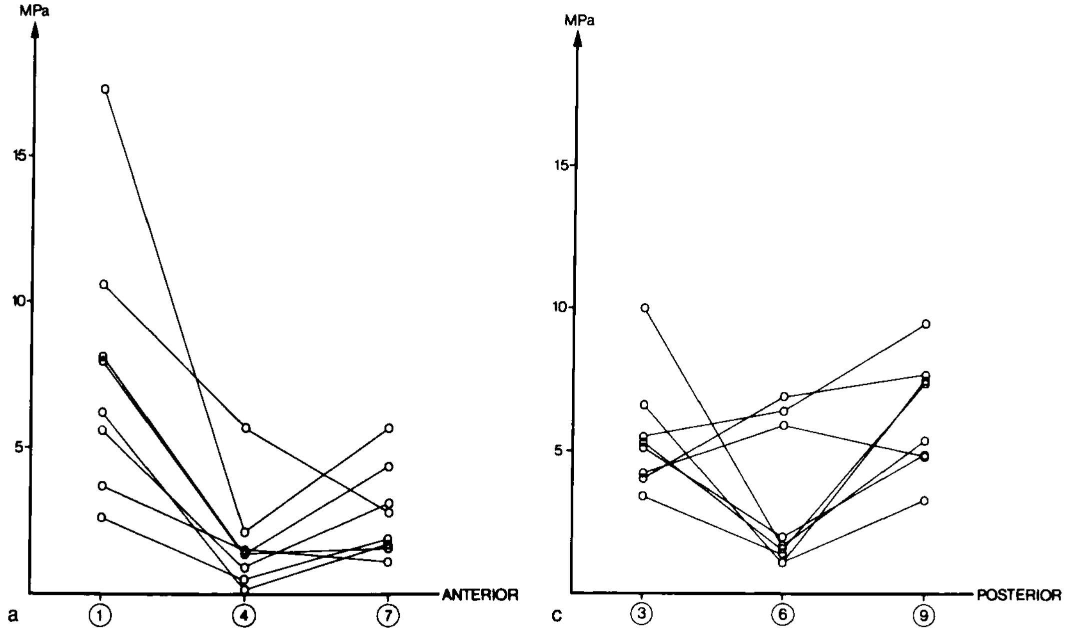
Calculation of energy absorption at fracture from the Instron-curves revealed the same pattern as that found for ultimate stress although the sagittal variation was less marked and there was no significant interaction between patterns of energy absorption in the frontal and sagittal planes. The same applies to the calculations of elastic modulus.

The penetrometer tests also showed a significant difference between knees. At the proximal level the variation in the frontal plane was highly significant ($F_{2,27}$ = 10.24, $P < 0.01$), while the sagittal variation was slightly less marked ($F_{2,27}$ = 4.21, $P < 0.05$). There was a significant interaction between the two ($F_{4,24}$ = 3.10, $P < 0.05$). At the distal level, sagittal variation was somewhat less marked, not reaching the level of statistical significance. The two horizontal levels measured did not differ significantly.

It is apparent that the penetrometer measurements yield a pattern closely resembling the pattern of ultimate stress. The pattern that emerges can be appreciated from Figures 5 and 6. Anteriorly, the trabecular bone is strongest medially, while posteriorly the reverse is true. Centrally, corresponding to the intercondylar area, the bone is relatively weak.

DISCUSSION

The pattern of proximal tibial cancellous bone compressive strength found in this study is consistent with the findings of Behrens et al. (1974). When mean values are considered, the overall ultimate stresses on the medial side exceed those on the lateral side by approximately 50%. Beneath the lateral condyle the posterior bone was



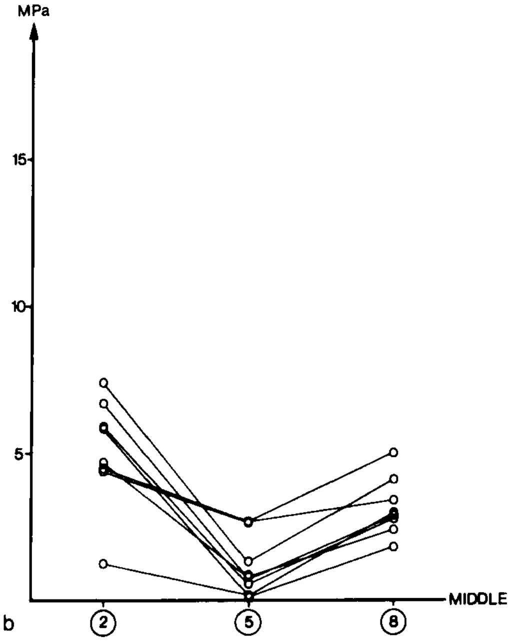
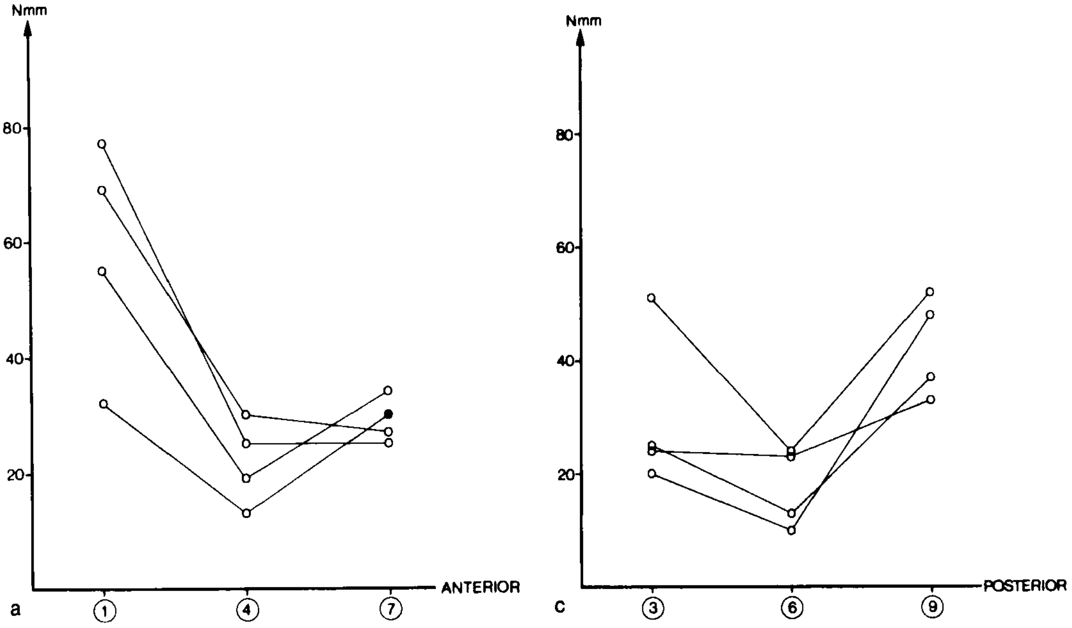


Figure 5a, b, c. Ultimate stress values for the proximal level of the eight knees tested in the Instron® machine. Numbered measuring sites refer to Figure 1.

strongest. Behrens et al. found that the bone beneath the medial condyle was slightly stronger centrally (corresponding to our position "2"), while in this study the anterior bone was slightly stronger. The absolute values of compressive strength reported by Behrens et al. are considerably higher than those reported here. The sources of bone are comparable and the difference is probably due to differences in measuring technique. In our study a bone plug was compressed over its whole surface area without lateral constraint, while in the former study the bone specimens were constrained laterally by embedding in methyl methacrylate.

Lindahl (1976), on the other hand, reported slightly lower compressive strength values, but did not specify the topography of the test specimens. Yuzuki (1977) tested knee joint surfaces by means of an Instron-type testing machine fitted with a large plunger; depth and penetrating force were recorded. Thus the principle of measuring bears some resemblance to that of the osteopenetrometer. Medial and lateral condylar strength were recorded. Medial strength generally exceeded lateral strength. The indentation



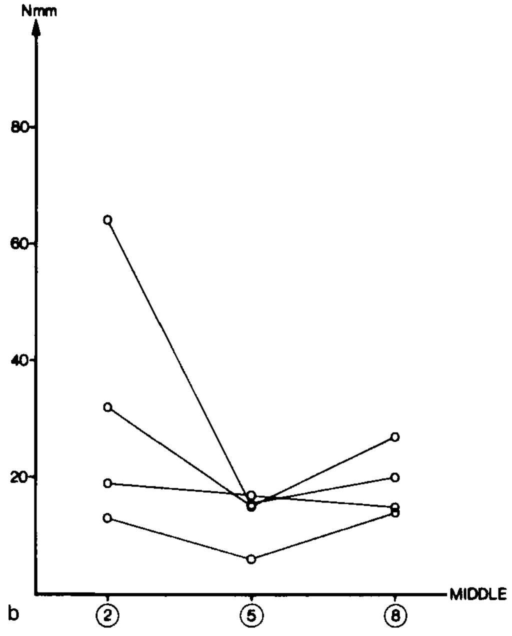


Figure 6a, b, c. Penetration work for the proximal level of the four knees tested with the osteopenetrometer. Numbered measuring sites refer to Figure 1. Filled circles represent estimated data.

studies of Bargren et al. (1978) showed a similar pattern of maximal bone strength medially and minimal strength centrally. Goldstein et al. (1980) reported on the variation of elastic moduli in the proximal tibia. The values and pattern were similar to those reported here.

Our findings do not indicate that bone strength diminishes from proximal to distal levels, as reported by Bargren et al. (1978) and Sneppen et al. (1981). This aspect is very important since it implies that the amount of tibial resection in resurfacing arthroplasty of the knee would be critical to the loading capacity of the knee and to the risk of mechanical loosening of the tibial component. Unfortunately, Bargren et al. (1978) examined the influence of horizontal level in only one knee, and the material reported by Sneppen et al. (1981) is equally limited. Further studies are required to clarify this problem.

The distribution of strength of the proximal tibia found in this and other studies supports the idea, known as Wolff's Law, that bone will adapt to functional demands, since it has been shown by several investigators that the normal knee during walking transfers considerably more load to the medial than to the lateral condyle – in spite of the fact that static analysis shows that the line of force-action is through the centre of the knee (Morrison 1970, Seirig & Arkivar 1975, Harrington 1976, Johnson et al. 1980, Nissan 1981).

The osteopenetrometer measurements closely reflected the pattern of ultimate stress. In a previous study (Sneppen et al. 1981) a satisfactory correlation was found between compression tests and osteopenetrometer tests. The principle employed in the osteopenetrometer thus seems to be a sound one, and since this instrument can be used for *in vivo* measurements during prosthetic replacement of the knee-joint, important knowledge about bone strength in osteoarthritis and rheumatoid arthritis may be gained.

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