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STUDIES ON MECHANICAL STRENGTH OF BONE

I. Torsional Strength of Normal Rabbit Tibio-Fibular Bone

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A method is described for testing torsional strength in small cortical bones at low velocities. The linearity and precision of the testing equipment, and the effect of the dimensions and chemical composition of the bone on torsional properties are analysed.

Rabbit tibio-fibular bones exhibited right-to-left differences in energy absorption capacity (up to 10.0 per cent), torsional rigidity (7.1 per cent), torque moment at fracture (6.3 per cent) and angular deformation (5.7 per cent). The scatter in energy absorption was more dependent on differences in angular deformation (strain) than on differences in torque moment (stress). No statistically significant dominance of either side could be observed.

The biomechanical properties of the bones were dependent on the body weight of the test animal and the transverse dimensions of the bone, but were not influenced by the small variations measured in the chemical composition of normal bone.

Key words: bone; bone strength; chemical composition of bone; experimental measurement of bone strength

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Bone is a heterogeneous and anisotropic material; its mechanical properties have been investigated extensively. For this purpose the bone is usually subjected to pure tensile or compressive forces or a combination of these two, as in bending or torsion.

Measurement of the torque capacity of tubular bone is a suitable method for investigation of mechanical properties because a torsional load exerts simultaneously tensile, compressive and shear forces, each acting in a different plane on the same region of the bone. Torque moment is constant in every section of the specimen tested and the result is not critically dependent on the position of the supports of the specimen, as in the bending test (Brooks et al. 1970, Burstein & Frankel 1971).

On the other hand, tests on the strength of osseous tissue have revealed a number of features which have to be considered in analysing the results. The results obtained are critically dependent on the rate of loading (McElhaney 1966, Burstein & Frankel 1968, Panjabi et al. 1973), the shape and structure of the test specimen (Dempster & Coleman 1961), the stage of mineralization of the bone (Vose 1962, Currey 1969), the relation between the fibre orientation and the forces acting (Ascenzi & Bonucci 1967, 1968, Vincentelli & Evans 1971) and the effects of the storage and post-mortem changes (Sedlin

& Hirsch 1966, Strömberg & Dalen 1976a).

However precise the mechanical equipment used for measurements, biological variations inevitably affect the results. Within a single species, differences in mechanical properties have been reported between the right and left paired bones (Puhl et al. 1972, White et al. 1974, Strömberg & Dalen 1976b).

During the course of studies on the healing of experimental fractures (Paavolainen et al., to be published) the need became evident for a reliable method with which to follow the increase in mechanical strength in healing bone. To ensure that the method devised gives valid results the present study was undertaken to investigate the precision and linearity of the torsional testing method and the biological variations which may influence the test results.

MATERIALS AND METHODS

Experimental animals

Fifteen healthy rabbits of various ages and of both sexes weighing from 2400 to 4850 g (mean 3275 + 682 g s.d.) were selected for the investigation.

After the animals had been killed with an overdose of sodium pentobarbitone, the tibiofibular bones were exarticulated and dissected out, with the periosteum intact. Between the various test procedures the bones were kept moist in 0.9 per cent NaCl solution at room temperature.

Each left and right bone was loaded until failure with external torsion along the longitudinal axis of the specimen.

Measuring equipment

A special apparatus for torsiometry was constructed in collaboration with the Technical Research Centre of Finland (Figure 1).

The proximal end of the bone specimen was held rigidly while the distal end was connected with the rotating head of the torsiometer. The torque moment was transmitted to the test specimen at an angular velocity of 3.6 degrees/second. Progressive deformation of the specimen was produced by turning the rotating head with a number of turns on the driver. The deformation was registered with a linear potentiometer. Two strain gauges connected to a Wheatstone bridge measured the magnitude of the torsional moment. The output from the Wheatstone bridge mounted directly on the distal end of the torsion shaft was displayed on a Peekle analyser (Peekle Universal Amplifier, type 591 DNH, Holland). The output from the analyser (magnitude of torsional moment) was further displayed on the vertical axis and the output from the potentiometer (angular deformation) on the horizontal axis of a paper recorder (Hewlett-Packard, type 7015 A). As the angular velocity was constant during each experiment, the torque moment was determined as a function of the angular deformation of the specimen (Figure 4).

Calibration of the torsiometer

The linearity of the measurements obtained with the equipment was evaluated with a calibration torque wrench connected to the torsiometer, exerting different known torques on the measuring

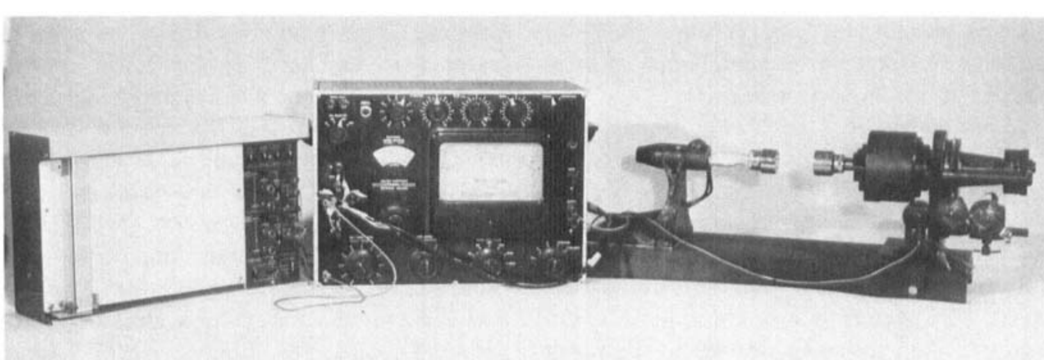


Figure 1. The torsional apparatus with the torsion device, Peekle micro-strain analyser and paper recorder.

device. There was a linear relation between the magnitude of the torque applied and the output signal of the analyser (Figure 2). Comparable results were obtained with left- and right-handed rotation on the turning head. Figure 2 depicts the relation between the various forces applied with the calibration torque wrench (kpm) and the percentage deviation of the corresponding output signals obtained. The data indicate that the proportional error increases exponentially as the magnitude of the force on the test specimen is reduced. At maximal loading of the test equipment (0.4 kpm) the proportional precision of the test equipment was 1.0–1.5 per cent. In the animal experiments, the torque applied to the bones ranged from 0.15 to 0.20 kpm. The measuring error of the torsiometer at this range of load was less than 3 per cent.

Mechanical testing of the bones

Before the test procedure the fibula was sawn through at the tibio-fibular junction leaving a stump of bone of 1-2 mm. Each end of the specimen was embedded in a nut with epoxy resin (Stabilit Express, Henkell, Germay) which has a mean hardening time of 20 minutes. The length of the shaft between the nuts was 8.5 centimeters in all specimens. The resin retained a constant volume during solidification. While the resin solidified the bones were laid against an L-shaped metal support, so that the nuts were held perpendicular to the specimen.

Connection between the bone specimen and the torsional equipment was achieved by inserting the nuts into two tightly fitting holders (Bahco 30 mm ϕ) firmly connected to the torsiometer (Figure 3). No motion could be observed between the test specimen and the equipment.

This rapid fixation procedure (30 minutes for a single specimen) made it possible to analyse the torque resistance of fresh bone without any storage procedure before testing. Close up photographs were taken of all the fractured specimens for later analysis of the fracture line (Figure 3).

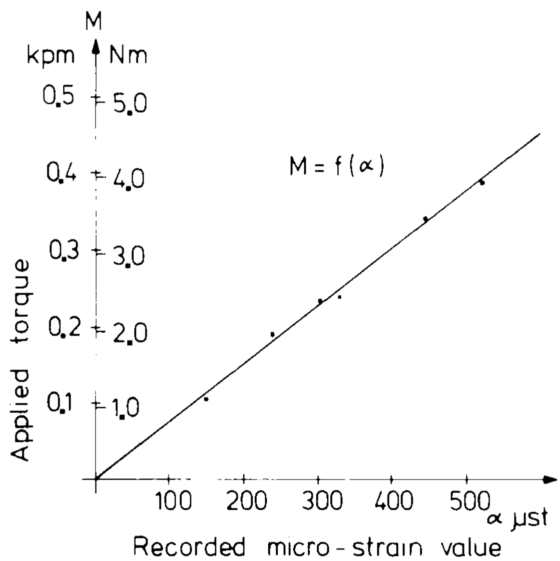
Biomechanical calculations

A typical load-deformation curve of a tibial bone is shown in Figure 4.

Maximum torque moment (M_t) was determined from the maximum deflection of the curve (to the nearest 0.1 mm) and expressed in Nm.

Maximum angle deformation (θ) was measured directly from the horizontal axis of the curve and expressed in degrees.

Energy absorbed until ultimate failure (W_t) of the bone was calculated from the area under the curve, which was measured with a planimeter (type HAFF 317). ($W_t = \int_0^\theta M_t . d\theta$) The values were expressed in Nm (Burstein & Frankel 1971).



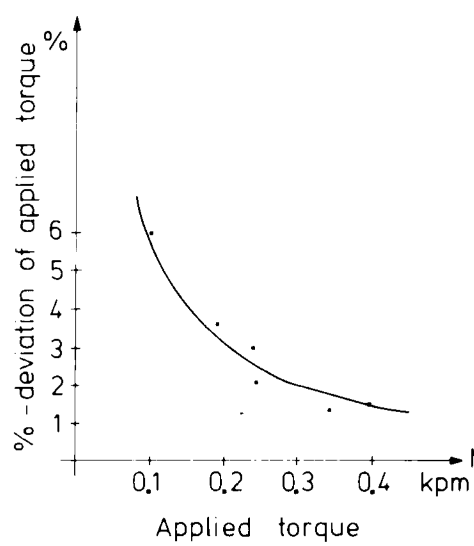


Figure 2. On the left: linear relation between force applied and results obtained. Ordinate: known torque applied; Abscissa: micro-strain value recorded.

Figure 2. On the right: the percentage deviation of the readings from the torque applied at various strengths.

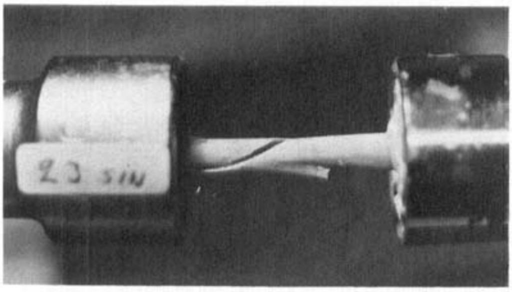


Figure 3. A typical spiral fracture after torsional loading of normal rabbit tibio-fibular bone. The crack cuts through the tibio-fibular junction at 45 degrees to the longitudinal axis of the specimen.

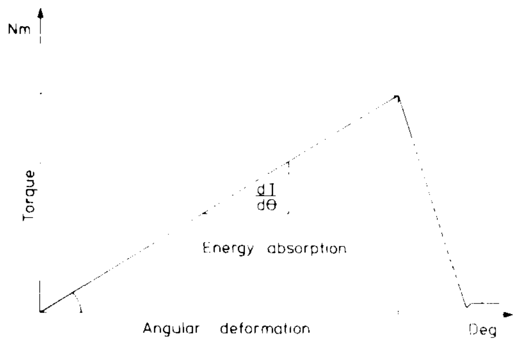


Figure 4. Load-deformation curve where torque moment is determined as a function of angular deformation. Energy absorption equals the area under the curve and torsional rigidity was determined from the slope of the linear portion of the curve.

Torsional rigidity (G) of the specimen was measured from the slope of the linear portion of the curve and expressed in Nm/degree. ($G = dM_t/d\theta_t$) (White et al. 1974, Panjabi et al. 1973).

The difference between results obtained for the right and left paired bones was expressed as

$$\left| \frac{(X)\ \text{right} - (X)\ \text{left}}{(X)\ \text{right} + (X)\ \text{left}/0.5} \right| \cdot 100 \quad \%\ \text{difference}$$

The data were processed with a computer and standard statistical methods were employed to test the significance of the results; $P > 0.05$ was taken as non-significant. The possibility that one measured variable influenced any other was examined by correlation analysis and the coefficient of correlation (r) calculated. The percentage error of the differences between the paired bones was calculated from duplicate determinations (standard error of the means, SEM) using the formula $SEM = \sqrt{d^2/2n}$, where d is the difference between duplicate measurements and n the number of pairs of bones measured.

Measurement of bone dimensions

At sacrifice, both tibio-fibular bones were radiographed on contact film. The entire length of the bone was measured directly from these radiographs.

After the torque test procedure, a standardized transverse section was sawn from the tubular bone at the level of the tibio-fibular junction. Contact microradiographs of these specimens were made on high-resolution X-ray film. The area of cross section and medullary cavity was planimetered from tenfold enlargements of these radiographs. The values so obtained were reduced mathematically to the actual size of the bone. The outer and inner diameters of the tube were determined with the same techniques.

Chemical analysis

Each fresh tubular section was weighed and stored in airtight containers and deep-frozen for chemical analysis.

The contents of calcium, phosphorus, hydroxyproline, hexosamines and total nitrogen were determined at the Department of Medical Chemistry, University of Turku, with the techniques previously described by Penttinen (1972).

RESULTS

The fractures produced were remarkably uniform in type. In all specimens there was a spiral fracture at 45 degrees to the longitudinal axis of the bone, with an additional spiral crack running up and down the bone beyond the actual limits of the fracture (Figure 3). The fracture appeared at the level of the tibio-fibular junction. In paired bones the two fractures seemed to be identical in appearance. The load-deformation curves, although very similar in shape, varied greatly in termination point. The mechanical properties of the bones in relation to the weights of the animals are presented in Table 1.

Correlation between body weight, bone dimensions and mechanical properties of bone

There was a highly significant correlation ($P < 0.001$) between body weight and the

Table 1. Torsiometric characteristics of rabbit tibio-fibular bones (with an angular velocity of 3.6 degrees/second)

Animal No.	Body weight (g)	Maximum torque moment (Nm) Right	Left	Maximum angular deformation (degrees) Right	Left	Energy absorption at fracture (Nm) Right	Left	Torsional rigidity (Nm/degrees) Right	Left
1	(2400)	0.68	0.81	3.60	3.51	0.03	0.03	0.19	0.23
2	(2610)	1.07	0.96	5.18	4.43	0.06	0.04	0.19	0.21
3	(2660)	1.33	1.38	6.37	6.94	0.09	0.10	0.19	0.20
4	(2730)	1.07	1.01	6.15	5.18	0.07	0.05	0.16	0.19
5	(2750)	1.38	1.12	7.11	7.07	0.10	0.09	0.20	0.19
6	(3005)	1.38	1.45	7.38	7.07	0.11	0.09	0.20	0.21
7	(3050)	1.08	0.96	5.14	5.00	0.06	0.05	0.21	0.19
8	(3100)	1.12	1.10	6.10	5.84	0.07	0.07	0.17	0.18
9	(3200)	1.30	1.23	7.46	6.59	0.10	0.08	0.16	0.18
10	(3250)	1.37	1.36	4.48	4.79	0.06	0.07	0.33	0.28
11	(3530)	1.22	1.26	5.71	5.88	0.07	0.08	0.22	0.22
12	(3800)	1.40	1.34	5.36	5.36	0.08	0.07	0.26	0.25
13	(4050)	1.21	1.36	4.08	4.14	0.05	0.06	0.30	0.30
14	(4150)	1.84	1.86	7.16	6.50	0.14	0.12	0.28	0.31
15	(4850)	1.90	1.89	6.19	6.01	0.12	0.12	0.33	0.31
Mean (s.d.)		1.29 (0.30)	1.27 (0.31)	5.83 (1.20)	5.60 (1.13)	0.08 (0.03)	0.07 (0.03)	0.23 (0.06)	0.23 (0.05)

Table 2. Correlations of the body weight of the animals and bone dimensions with the biomechanical properties of rabbit tibio-fibulae. Correlation coefficients and significance levels are presented and, if negative, marked −.

	Maximum torque moment	Maximum angular deformation	Energy absorption at fracture	Torsional rigidity
Body weight	0.794 (+++)	0.092 (N.S.)	0.552 (++)	0.773 (+++)
Entire cross-sectional area	0.400 (+)	−0.240 (N.S.)	0.098(N.S.)	0.647 (+++)
Area of cortical bone	0.351 (N.S.)	−0.320 (N.S.)	0.037 (N.S.)	0.679 (+++)
Bone length	0.500 (++)	0.381 (+)	0.482 (++)	0.341 (N.S.)
Outer diameter of tubular bone	0.185 (N.S.)	0.272 (N.S.)	0.043 (N.S.)	0.480 (++)
Inner diameter of tubular bone	0.327 (N.S.)	0.045 (N.S.)	0.171 (N.S.)	0.389 (+)

N.S. = not significant
(+) = $P < 0.05$
(++) = $P < 0.01$
(+++) = $P < 0.001$

entire cross-sectional area at the tibio-fibular junction, and between body weight and the area of the medullary cavity in the same area. A significant correlation ($P < 0.01$) could be observed between body weight and cortical bone area.

The body weight of the animal showed a statistically highly significant correlation ($P < 0.001$) with the maximum torque moment and the torsional rigidity (Table 2). The corresponding values for energy absorption were statistically significant ($P < 0.01$), but for angular deformation statistically non-significant.

The torque moment and energy absorbed at fracture seemed to be independent of the transverse dimensions of the bone. The only significant correlation ($P < 0.01$) was with the initial length of the bone.

Torsional rigidity of the bone, on the other hand, was proportional both to the entire cross-sectional area of the bone and to the area of cortical bone ($P < 0.001$). The correlation with the outer diameter of the tubular bone was statistically significant ($P < 0.01$).

The angular deformation at fracture was independent of the dimensions of the bone.

Variation between right and left bones

The difference between the right and left tibiae is shown in Table 3. No variable showed a significant left-right dominance. The standard error of the means of the percentage differences in Table 3 reflects the combined error of both the testing equipment and the biological variation between the bone specimens.

The interrelationship between the biomechanical variables was further tested by linear regression analysis. Since the standard error of the means of the differences was greatest for energy absorption, these values were plotted against the corresponding values for differences in torque, and differences in angular deformation at fracture. The respective coefficients of determination (r^2) were 0.37 and 0.72. This indicates that great variation in angular deformation, i.e. strain on the bone during torque, will be deflected by wide variations in energy absorbed at fracture, whereas similar variations in the torque values at fracture will have only a minor influence on the values of energy absorbed.

Chemical composition of the bone

The results of chemical analysis of the cortical bone specimens are shown in Table 4. The amounts of calcium, phosphorus, hydroxyproline, hexosamines and total nitrogen varied within narrow limits. When the chemical components were expressed as mg/g dry weight of bone there were no statistically significant differences between the samples from the right and left paired bones. Neither were there any differences in the concentrations of the above-mentioned parameters at any weights of the test animals.

Table 3. Computed differences between the paired right and left rabbit tibio-fibulae

Variable	Mean value of the % difference	P (t test)	Standard error of means of the % difference
Torque at fracture	1.15 %	0.65 (N.S.)	6.34 %
Angular deformation at fracture	3.50 %	1.85 (N.S.)	5.68 %
Energy absorbed at fracture	5.12 %	1.66 (N.S.)	10.0 %
Torsional rigidity	− 2.77 %	0.66 (N.S.)	7.08 %

Table 4. Chemical composition of rabbit tibio-fibulae. Data of right and left paired bones expressed as mg/g dry weight of bone.

Bone	Calcium (s.d.)	Phosphorus (s.d.)	Hydroxyproline (s.d.)	Hexosamines (s.d.)	Nitrogen (s.d.)
Right	256.5 (15.9)	119.6 (4.5)	28.7 (1.1)	2.04 (0.28)	34.7 (1.5)
Left	248.5 (22.3)	118.1 (3.1)	28.2 (1.2)	2.19 (0.39)	36.9 (5.5)
t test for paired bones	N.S.	N.S.	N.S.	N.S.	N.S.

Correlation analysis revealed no significant correlations between the mechanical properties and chemical composition of the bones.

DISCUSSION

Bone is a composite material exhibiting elastic, viscoelastic and plastic properties (Sedlin 1965, Burstein et al. 1975). It can resist tensile forces as compared to compressive forces in a ratio of about 3:4 (Currey 1970). Consequently the great majority of cortical bone fractures are caused by tensile forces, regardless of whether the force responsible is tension, bending or torsion. The ultimate tensile strength of bone is less than the ultimate shear strength. Therefore in torsion, shear forces result in tensile and compressive forces acting at angles of 45 degrees to the plane of shear (Figure 5), and a spiral fracture occurs at 45 degrees to the axis of the bone.

Bone can absorb noticeably more energy when force is applied at high velocity (Sammarco et al. 1971, Panjabi et al. 1973). Hence bone behaves as a tough material at slow strain rates and as a brittle material at high strain rates. The microscopical appearance of the fracture line has been reported to be different in low- and high-velocity fractures (Piekarski 1970). Halving and doubling of low velocities, as in the present study, does not significantly change the maximum torque capacity (Strömberg & Dalen 1976b).

Paired bone specimens exhibited varying mechanical properties. According to many investigators, however, right-left differences in bones from different animals and human

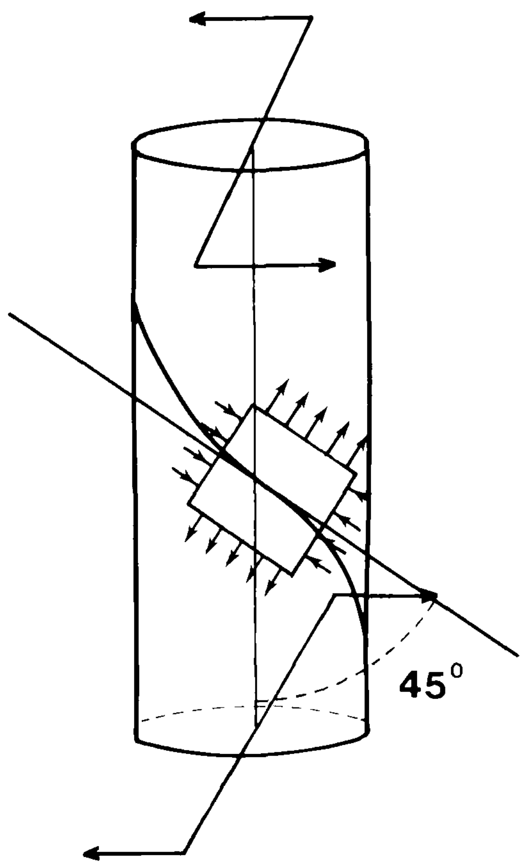


Figure 5. Shear forces arising from torsion, resulting in tensile and compressive forces at 45 degrees to the plane of shear. A spiral fracture will occur at 45 degrees to the axis of the bone.

cadavers have no statistical significance (Currey 1969, Puhl et al. 1972, White et al. 1974, Strömberg & Dalen 1976b). This was confirmed in the present study. However, the right-left variation in mechanical properties of paired bones must be known in any biomechanical investigation in which the contralateral bones are to be used as controls. Strömberg & Dalen (1976b) reported the variation for torque capacity in canine femora to be 3.1 per cent, compared with 6.3 per cent in this report. The difference may be due to the different species used and to the almost ten-fold greater torsional moment used in their investigation.

The results suggest great variation in the amount of energy absorbed until fracture. This agrees with the observations reported by Bechtol (1959) in bending tests and Puhl et al. (1972) in torsional testing. The present results show that bone can sustain very little angular deformation without fracturing. Accordingly, changes in angular deformation lead to considerable variation in the energy absorption capacity of bone.

A high correlation was established between body weight and the dimensions of the tubular bone. The biomechanical variables measured, with the exception of angular deformation, were highly dependent on body weight, which corroborates the observations made by Lindsay & Howes (1931). Thus in a series of experimental animals of different weights torsional properties of whole bone specimens should be corrected for the weights of the animals, in order to arrive at comparable results.

As was expected, these normal animals showed little variation in the chemical composition of the bone, and no significant differences were observed between paired bones. In normal bone specimens the dimensions of the bone are more important for the maintenance of torsional strength than are the changes in the chemical content of the bone. With the known error of the test equipment and the biological variations of paired bones, this torsiometric assessment of bone strength is a suitable method for analysis of biomechanical bone characteristics.

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REFERENCES

Ascenzi, A. & Bonucci, E. (1967) The tensile properties of single osteons. *Anat. Rec.* **158,** 375–385.

Ascenzi, A. & Bonucci, E. (1968) The compressive properties of single osteons. *Anat. Rec.* **161,** 377–390.

Bechtol, C. O. (1959) Bone as a structure. *Metal and engineering in bone and joint surgery*, ed. Bechtol, C. O., Ferguson, A. B. & Laing, P. G. Williams & Wilkins, Baltimore.

Brooks, D. B., Burstein, P. H. D. & Frankel, V. H. (1970) The biomechanics of torsional fractures. *J. Bone Jt Surg.* **52**-A, 507–514.

Burstein, A. H. & Frankel, V. H. (1968) The viscoelastic properties of some biological materials. *Ann. N. Y. Acad. Sci.* **146,** 158–165.

Burstein, A. H. & Frankel, V. H. (1971) A standard test for laboratory animal bone. *J. Biomech.* **4,** 155–158.

Burstein, A. H., Zika, J. M., Heiple, K. G. & Klein, L. (1975) Contribution of collagen and mineral to the elastic-plastic properties of bone. *J. Bone Jt Surg.* **57**-A, 956–961.

Currey, J. D. (1969) The mechanical consequence of variation in the mineral content of bone. *J. Biomech.* **2,** 1–11.

Currey, J. D. (1970) The mechanical properties of bone. *Clin. Orthop.* **73,** 210–231.

Dempster, W. T. & Coleman, R. F. (1961) Tensile strength of bone along and across the grain. *J. appl. Physiol.* **16,** 355–360.

Lindsay, M. K. & Howes, E. L. (1931) The breaking strength of healing fractures. *J. Bone Jt Surg.* **13,** 491–501.

McElhaney, J. H. (1966) Dynamic response of bone and muscle tissue. *J. appl. Physiol.* **21,** 1231–1236.

Panjabi, M. M., White III, A. A. & Southwick,

W. O. (1973) Mechanical properties of bone as a function of rate of deformation. *J. Bone Jt Surg.* **55**-A, 322–330.

Penttinen, R. (1972) Biochemical studies on fracture healing in the rat. *Acta chir. scand.*, Suppl. 432.

Piekarski, K. (1970) Fracture of bone. *J. appl. Physiol.* **41,** 215–223.

Puhl, J. J., Pietrowski, G. & Enneking, W. F. (1972) Biomechanical properties of paired canine fibulas. *J. Biomech.* **5,** 391–397.

Sammarco, G. J., Burstein, A. H., Davis, W. L. & Frankel, V. H. (1971) The biomechanics of torsional fractures: the effect of loading on ultimate properties. *J. Biomech.* **4,** 113–117.

Sedlin, E. D. (1965) A rheologic model for cortical bone. A study of the physical properties of human femoral samples. *Acta orthop. scand.*, Suppl. 83.

Sedlin, E. D. & Hirsch, C. (1966) Factors affecting the determination of the physical properties of femoral cortical bone. *Acta orthop. scand.* **37,** 29–48.

Strömberg, L & Dalen, N. (1976a) The influence of freezing on the maximum torque capacity of long bones. An experimental study on dogs. *Acta orthop. Scand.* **47,** 254–256.

Strömberg, L. & Dalen, N. (1976b) Experimental measurement of maximum torque of long bones. *Acta orthop. scand.* **47,** 257–263.

Vincentelli, R. & Evans, F. G. (1971) Relations among mechanical properties, collagen fibres and calcification in adult human cortical bone. *J. Biomech.* **4,** 193–201.

Vose, G. P. (1962) The relation of microscopic mineralization to intrinsic bone strength. *Anat. Rec.* **144,** 31–36.

White III, A. A., Panjabi, M. M. & Hardy, R. J. (1974) Analysis of mechanical symmetry in rabbit long bones. *Acta orthop scand.* **45,** 328–336.

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