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## FACTORS AFFECTING THE DETERMINATION OF THE PHYSICAL PROPERTIES OF FEMORAL CORTICAL BONE<sup>1</sup>

*By*

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Many methods have been used for the preparation, storage, and testing of samples in the determination of the physical properties of bone (1, 3, 9). The methods and conditions have varied or are sometimes inadequately described, so that it becomes difficult to compare the works of various authors. The desire to provide a standard method of preparation, storage, and testing of bone specimens furnished the framework of this study. Here, a summary is presented of the interim results of a continuing investigation of the physical properties of the human femoral cortex obtained from autopsy material. Some of the general mechanics terms used in the text are summarized in Appendix 1.

### MATERIAL AND METHODS

The entire mid-femoral diaphysis from twenty adult subjects was removed at routine post-mortem examination that was performed on the day of death or the day after. The segments were 15 cm long and began 5 cm distal to the base of the lesser trochanter. After removal, the segments were worked in the fresh state or stored at  $-20^{\circ}\text{C}$  in Ringers solution until they could be handled.

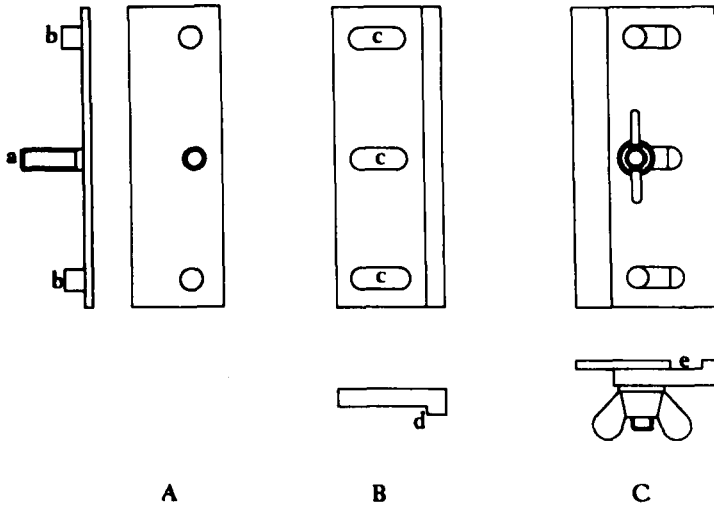
The general method of reduction of the segments to test size is as follows: It is placed in Ringer's solution at room temperature and it is kept in Ringer's solution at all times when it is not actively being handled. It is first sectioned, in its long axis with a handsaw or a bandsaw under a constant cold aqueous drip. Excess

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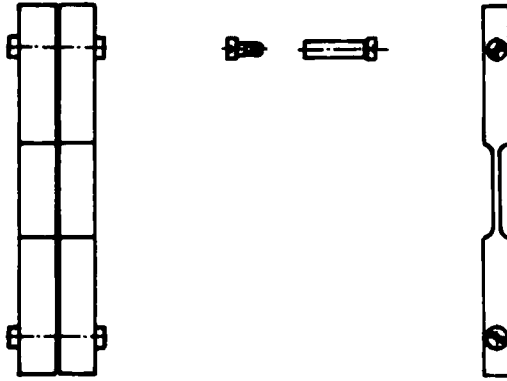
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**Figure 1.** Several views of apparatus used to make rectangular segments of bone. A. Top and lateral view of adjustable plate showing screw stud (a) and excursion studs (b). B. Similar views of base plate showing grooves for screw and excursion studs (c) and height control bar (d). C. Top and lateral views of assembled apparatus, showing slot (e) for placing of bone specimen.

The rough sextant or octant of bone is placed in slot, and then secured by means of the wing nut. It is then ground with repeated turning of  $180^\circ$  until flush with the apparatus. This produces one dimension. The specimen can then be shifted to another apparatus for producing a different size in the right angle pair of sides or worked in the same apparatus if square sides are desired. The apparatus should be made of very hard steel to reduce wear. When wear becomes apparent the plate and height control bar can be replaced with little difficulty.

heat production is thereby diminished. The number of longitudinal strips and their size is varied according to the needs of the specific experiment. It is usually possible to obtain 15 strips which are then labelled according to the quadrant of origin and placed in Ringer's solution. These strips can then be further reduced in size by sawing. The total number of final specimens that can be obtained varies with the desired length and thickness. The strips are then placed in a special holding tool (Figure 1) and ground under cold water using water-proof silicon carbide paper or a universal drill fitted for grinding at low speeds. In practice, the drill is used for rough shaping of the specimen, and manual grinding for final shaping. The specimens are repeatedly turned during the grinding process to insure mutually flat and perpendicular sides and care is taken so that bone from the center of the cortex remains after the grinding process. With the use of holding tools of various sizes, we can prepare specimens from  $0.5 \text{ mm} \times 1.0 \text{ mm}$  to  $5 \times 15 \text{ mm}$  in cross-section dimensions, the major limitation being the thickness of the cortex. Specimens with greater than 1.5 per cent variation in cross-section dimen-



*Figure 2. Diagram of side and front view and screw assembly of apparatus used to reduce central area of specimen. A specimen is prepared of desired dimensions. A typical specimens in this study is 5 mm broad, 2 mm thick, and 50 mm long. This small plank is placed in the slot of the apparatus, and screws are tightened. It is then mounted in a vice under a cold aqueous drip, and with a tempered file, the central area is reduced until it is flush with the reduced central portion of the apparatus. The apparatus can be made of varying sizes to accommodate specimens of different thickness or length. As in previously shown apparatus, it must be made of very hard steel.*

sions throughout their length are discarded or reworked. If a specimen is to be tested in tension until failure, the central area is reduced by the use of a holding tool of the type shown in Figure 2. The method is rapid, simple, and requires little experience to acquire the ability to produce precise specimens.

After the specimen preparations are completed, the measurements of the cross-section dimensions are performed with a CEJ friction release micrometer with an accuracy of 0.005 mm. After the measurements are completed, the specimen is ready for testing. Microscopic examination of undecalcified cross-sections of 50 specimens indicated that a normal complement of osteocyte nuclei was present and the staining pattern was normal. Accordingly it is felt that the method of preparation had not had a deleterious effect on the bone.

Bending, tension, and compression tests are performed on an Instron TT-CM floor model tensile test machine that permits simultaneous recording of the load being applied and deformation produced, with an accuracy of  $\pm 0.5$  per cent (14). It is calibrated before each test run for accuracy of load recording, recorder speed and excursion of the load heads. Load is determined from the recorder tracing, and deformation either calculated from the tracing or read directly from the machine. Special jaws fitted with silicon carbide paper enable specimens for tension testing to be held without detectable slippage. Bending specimens can be subjected to bending load either as a cantilever or doubly-supported beam with central or excentric load via a special head for the machine which has been designed to function as a clasimeter or cantilever load support. Compression tests are performed with the standard Instron Compression Cage. All tests are performed in a room with controlled temperature and humidity at  $21^{\circ}\text{C} \pm 1^{\circ}$  and 66 per cent  $\pm 2$  per cent respec-

tively. Bending tests are performed submerged in Ringer's solution, under controlled temperature via a cyclotherm pump. Compression and tension tests are performed in air. Prior to testing, all specimens are warmed to 37° C in Ringer's solution for one hour, unless the specific requirements of the test dictate room temperature and hydration. A specimen for bending can be placed on its supports in fifteen seconds as can the compression specimens. Tension specimens require approximately three minutes for this procedure. Unless otherwise stated, all tests indicated in the text are bending tests to failure performed with end-supports, unfixed, and progressive central load with a rate of deformation 1 cm/minute at 37° C in Ringer's solution. The formulae used for calculation of the physical properties are presented in Appendix 2.

Standard statistical methods were utilized in evaluating results (20). The 5 per cent level of probability was chosen as the criterion of statistical significance.

## EXPERIMENTS

The problems that have been investigated are presented here in the form of specific questions with each experiment being detailed as the question is presented.

### *Is there any Difference between Testing at Body Temperature and at room temperature?*

Seventy-seven specimens from three subjects were divided into two groups and closely matched as regards quadrant of origin. One group was tested at 37° C and the other at 21° C. No significant differences were noted relative to maximum stress and energy absorbed to failure. The modulus of elasticity was 5 per cent higher in one of the subjects at room temperature, and unchanged in the others. A significant, 6 per cent increase in total deflection to failure was noted in the group tested at 37° C. These findings coupled with the observation of *Smith & Walmsley* (19) has led us to adopt 37° C as a standard temperature condition when the requirements of the test permit.

### *What is the Effect of Short-term Air Drying on the Physical Properties?*

One-hundred thirty-seven specimens from five subjects were studied. These, as previously, were closely matched as regards site of origin. All tests were performed at room temperature without previous warming to body temperature. Small groups were tested under Ringer's solution and at varying times in air, ranging from five minutes to one hour. One group was dried in an incubator at 105° C for one week and then tested.

The results showed that after ten minutes in air, specimens from

some of the subjects began to show increase in strength, an effect which was general after fifteen minutes and pronounced in one hour.

The average value for maximum stress in specimens tested under Ringer's solution was 19.3 kg/mm<sup>2</sup>, whereas those specimens tested after one hour in air had an average value of 23.1 kg/mm<sup>2</sup>. This was significant beyond the 1 per cent level. After 30 minutes in air, the differences in values were of borderline significance ( $0.10 > P > 0.05$ ). Energy absorbed to failure increased after drying, but the degree of change was not statistically significant. The modulus of elasticity showed no change associated with air drying up to one hour. Since this observation appears to be incompatible with the above, it is being investigated further.

The specimens from three subjects that had been incubated for one week prior to testing, when compared to wet tests from the same subjects showed that: there was no significant change in maximum stress; the modulus of elasticity increased significantly; and energy absorbed to failure and total deflection decreased significantly.

There may be a decrease in the rapidity to the effect of air-drying if the specimens are made larger. In order to circumvent the problem, it was decided to test under fluid, or as quickly after removal from fluid as possible.

#### *Does Freezing Prior to Testing Produce any Effect upon the Physical Properties?*

Seventy-four specimens from three subjects were prepared as rapidly as possible following the obtaining of bone from autopsy. One-half were tested approximately three hours after removal from the body, and the others were placed in a deep freeze at  $-20^{\circ}\text{C}$  for three-four weeks and tested after thawing. There was a 5 per cent increase in the average strength of the samples that had been frozen from 16.7 kg/mm<sup>2</sup> to 17.6, which was not significant and no change in any of the other parameters mentioned. These results, coupled with Frankel's observations on intact femurs, lead us to feel that we do not significantly change the physical properties by prior freezing if the specimen is adequately hydrated and thawed before testing (10).

#### *What is the Effect of Fixation of the Specimen in Formalin?*

Fifteen specimens from one subject were prepared fresh and then progressively loaded in tension at 0.1 cm/minute to 8-9 kg, such loads being well below those required to produce permanent deformation

as demonstrated by additional tests to failure of specimens from the same subject. After the initial test, the specimens were placed in 10 per cent formalin solution for three weeks, and then retested. The modulus of elasticity was determined in both instances and no significant change was noted. There is disagreement relative to the effect of formaldehyde fixation of specimens (2, 7, 15) and although the findings of this experiment are in agreement with those of *McElhaney* (15) relative to the modulus of elasticity, it is felt that whenever possible, bone should be tested in the unfixed state.

*With small Specimen Testing, is there any Effect that can be Attributed to varying the Specimen Size?*

Thirty specimens  $1.5 \times 1.0 \times 30$  mm were compared to 70  $2 \times 2 \times 30$  mm specimens from the same subjects. No significant differences were noted in any physical property that could be attributed to this variate. However, since errors in tolerance and measurement are absolutes, their relative importance increase as the specimens are made smaller. One must, therefore, balance this consideration against the desire to obtain a large number of specimens from any one subject.

*What are the Changes in Cross-section Dimensions of the Specimen due to Testing?*

This question is necessitated by the fact that it is usually more convenient to measure the dimensions after it has been tested than before, since there is some urgency involved in measuring the sample when one desires to test it as rapidly as possible following removal from the body. This is coupled with the fact that a change in dimensions occurs in isotropic materials during testing and after tests are completed (16). Thus if one uses the initial cross-section measurements in the calculations of maximum stress, the value will differ from that obtained utilizing the measurements obtained after failure. Seventy specimens  $2 \times 2$  mm in cross-section dimensions were marked at their mid-point, measured, and then loaded to failure on the mark. They were then remeasured as close as possible to the mark. There was on average a 2 per cent decrease in the cross-section area near the fracture site after testing which was not significant or consistent, but more important, splintering occurred in a sufficiently large number of cases to make adequate measurement near the fracture impossible. Accordingly, in bending tests, we measure, mark, and load on the mark.

In specimens that are to be tested in tension, it is impossible to predict the exact location of the fracture in the test area, so that a comparative experiment such as the above cannot be performed. We have adopted the following procedure: Five pairs of measurements are made from one end of the file to the other at equally spaced intervals and marked accordingly. If the specimen fails on a mark, the appropriate measurement is utilized in the calculations. If it fails between a pair of marks, the average is used for the calculations. This method is used since it is not known how much of the waisting that occurs in a tension test will recover immediately after failure, thus preventing the observer from knowing whether he is calculating the engineering stress, true stress, or some value between the two.

Specimens that are tested in compression present no problem, since, when they fail, it is often by a type of fracture that leaves little to measure. The dimensions are determined beforehand.

#### *What is the Effect of varying the Distance between Supports in Bending Bone as an End-supported Beam?*

In isotropic materials, the strength and modulus of elasticity vary with the distance between supports when being bent as end-supported beam (17). Shear stresses increase in loading of very short beams (17). Eight specimens from two subjects,  $2 \times 2 \times 60$  mm were measured at their mid-point and then loaded up to one Kg six times, with 15 minutes between each loading. The distance between supports was changed between each loading from a ratio of 6:1 (Distance: thickness of specimens) initially, to ratios of 10, 15, 20, 25, and 30:1. Between loading, the specimens were kept in Ringer's solution at 37° C. It was found that there was a significant decrease in the modulus of elasticity with ratios less than 15:1, and a slight decrease with the ratio of 30:1. There was essentially no difference between the ratios of 15, 20, and 25:1. We customarily use the 15:1 ratio in testing, since with thicker specimens (3 or 4 mm in thickness) this decreases the length requirement.

#### *What is the Effect of Repeated Loading on the same Specimen?*

Thirty specimens from three subjects were tested in the following manner. The approximate breaking strength was determined for the specimens of each subject by loading three extra specimens to failure. A load was then selected for each subject that was approximately 35 per cent of the breaking load. The selected load was applied to the

specimens from a subject two or three times, with at least one minute intervals between the removal of the load and its reapplication. The modulus of elasticity was calculated for each case of loading, and no significant differences were noted between first, second or third trials. This should not be interpreted to mean that repetitive loading does not effect the physical properties. Currently, we are engaged in the determination of the number of repeat applications of a static load that can safely be undertaken before an effect is demonstrated.

*What is the Effect of the Rate of Deformation upon the Physical Properties?*

In a series of compression tests, *McElhane* (16) showed that the modulus of elasticity and strength of human and bovine bone vary with the rate of strain. Our experiments relative to this question are as follows: Twelve specimens from one subject  $2 \times 2 \times 50$  mm were loaded progressively as a cantilever to 250 grams, at a rate of 0.1 cm/minute. The load was released, and two minutes were allowed to elapse. The specimens were then reloaded to 250 grams, this time at a rate of 1.0 cm/minute. The position of each specimen was not changed between loadings, and the test conditions relative to temperature and hydration were constant at  $37^\circ$  and submerged. The modulus of elasticity was calculated for each instance, and an average increase of 7.6 per cent was found for the more rapid loading rate. This difference was highly significant ( $p < 0.001$ ).

Further tests using 6 tension specimens and 5 bending specimens loaded centrally as a supported beam substantiated the finding that modulus of elasticity increase with a more rapid rate of deformation. It thus becomes necessary to accompany all data presentations relative to physical properties with information relative to the deformation rate. There is at present insufficient data, in the current study or that cited, to determine the exact relationship between the modulus of elasticity and the rate of deformation.

*Is there any Difference in Physical Properties that can be Accounted for by Quadrant of Origin within the Femoral Shaft?*

Evans has shown that significant differences can be demonstrated between the physical properties of different bones and separated regions of the same bone (7, 9). All specimens in this study came from near identical sites in the femoral mid-shaft, and all specimens were coded from the standpoint of quadrant of origin (posterior, lateral,

etc.) at the beginning of the study. The data from thirteen subjects was analyzed with regard to this variate. It was found that the lateral quadrant specimens were strongest, (19.3 kg/mm<sup>2</sup>), and posterior weakest, (17.8 kg/mm<sup>2</sup>), with anterior and medial being second and third respectively, (18.9 & 18.7). These differences were significant, ( $P < 0.01$ ) and the ranking was fairly consistent, *i.e.* the lateral quadrant specimens were strongest in 6 of the subjects, and the posterior weakest in 8. (Coefficient of concordance = 0.30). The values for the medial quadrant closely approximated the mean value for a subject in most instances. Therefore, if large numbers of specimens cannot be tested, or one cannot obtain the entire segment of diaphysis, the medial quadrant appears to be the best choice to obtain a valid idea of the properties of the mid-femoral diaphysis.

*Can the Variation in Physical Properties be Accounted for by Features of the Microscopic Anatomy?*

Undecalcified cross-sections of 125 wet-tested specimens were prepared on either side of the fracture site as close to the fracture as possible by a modification of Frost's method and then stained with 1 per cent basic fuchsin for at least 48 hours (11, 12). The first 50 sections to be completed were measured with an eyepiece micrometer at low magnification, and the measurements compared to the previously recorded measurements for the specimens prior to sectioning. No differences were noted, indicating that shrinkage during preparation and mounting was nil.

All sections from the 125 specimens were examined at  $320 \times$  magnification utilizing a Zeiss I integrating eyepiece, and completely scanned several times and the volume of the specimen occupied by Haversian canals determined (13, 18). This volume varied from 2 per cent to 16 per cent in different specimens. No correlation was noted between the volume and maximum stress, total strain, energy absorbed to failure, and yield time. There was a low-grade correlation with the modulus of elasticity. The findings agreed in part with those reported by Vose (21) and Evans (8).

Do these findings indicate that the microscopic anatomy cannot account for the variations? Not necessarily. It is probable that the arrangement of the Haversian systems within the specimen is more important than is the total volume or number of canals. In order to explain this assumption, it is necessary to digress.

*Table 1. Some physical properties of Data for some physical properties of femoral cortex in specimens from 14 subjects tested progressive central load at a rate of 1.0 cm/minute at 37° in Ringer's solution. Tension loaded progressively at*

Case	Age Sex	Cause of Death	Maximum Stress Kg/mm <sup>2</sup>	
			Bending	Tension
I*	34 M	Suffocation	19.6 ± 1.9§	8.0
II	34 M	Myocardial Infarction	17.9	8.9
III	41 F	Carcinomatosis	20.6 ± 3.5	
IV	46 F	Myelomatosis	21.2 ± 1.9	
V	47 F	Melanoma	17.5 ± 1.0	
VI	55 M	Pneumonia	19.0 ± 2.1	
VII	57 M	Hepatoma	18.7 ± 1.9	
VIII*	62 M	Pneumonia	19.7 ± 1.6	9.9 ± 1.5
IX*	67 M	Trauma	20.3 ± 2.7	83 ± 1.6
X*	69 M	Myocardial Infarction	17.6 ± 1.3	8.3
XI	74 F	Myocardial Infarction	18.8 ± 1.3	
XII*	76 M	C V A	21.3 ± 3.3	9.5
XIII	77 M	Abdominal Abscess	11.7 ± 1.4	
XIV	91 M	Myocardial Infarction	13.9 ± 3.4	

§ One Standard Deviation. Standard Deviations were not calculated for groups smaller

In the calculation of the moments of inertia in this study, an homogenous material is assumed, although this is obviously not the case in bone. In order to calculate a true moment of inertia for a porous material, the moment of inertia of each void (Haversian Canals in this instance) in relation to the axis of loading must be determined, and the combined moments for all of the voids subtracted from the moment assumed from the outer dimensions and shape of the specimen.

The above refers to calculation of the physical properties in bending tests. In tension testing, it is assumed that stress is homogenous throughout the length of the test area. This can only be true if the Haversian canals are homogeneously dispersed throughout the test area which is not the case in small samples of bone. In addition, the presence of a canal at the surface of the specimen will lead to an increase in stress at that point, and may cause failure (9). So, at best, one only has an estimate of the stress at the site of failure or throughout the length of the file.

It has been indicated that there is no correlation between Haversian

*fresh samples of mid-femoral cortex.*

in the wet, warm, state. Bending tests were performed with unfixed, end support, and tests were performed in air immediately after removal from 37° Ringer's solution and a rate of 0.1 cm/minute.

Modulus of Elasticity Kg/mm <sup>2</sup> × 1000		Energy Absorbed To Failure Kg M c/mm <sup>3</sup> × 10 <sup>3</sup>		Number Samples	
Bending	Tension	Bending	Tension	Bending	Tension
1.58 ± .16	.72	4.58 ± 1.03	14.2	46	8
1.58	.58	2.98	12.9	4	4
1.77 ± .30		5.29 ± 1.74		20	
1.97 ± .30		4.46 ± 1.36		22	
1.41 ± .16		4.63 ± .91		29	
1.57		3.06 ± .95		12	
1.69 ± .19		3.64 ± .91		20	
1.63 ± .17	.66 ± .12	4.01 ± .87	18.9 ± 5.7	36	16
1.71 ± .22	.67 ± .08	4.55 ± 1.86	11.0 ± 4.3	27	10
1.44 ± .15	.53	3.84 ± .70	14.9	19	9
1.68 ± .12		3.60 ± .95		24	
1.77 ± .30	.45	5.50 ± 1.57	17.7	28	5
1.06 ± .15		2.19 ± .45		14	
1.30 ± .29		2.89 ± 1.32		19	
				318	52

than 10 \* Specimens from both femurs are included in the data.

canal volume and the physical properties. This is true in the relation to specimens that have a canal volume of 4–10 per cent, (80 per cent of the total number examined) but in the extremes, *i.e.* very dense or very porous specimens, one could predict corresponding changes in strength and modulus of elasticity.

Thus the data lead to the conclusion, that in order to account for the physical properties of wet bone on a microscopic basis, one must be prepared to reconstruct the three dimensional microanatomy of the of the specimen in the large majority of instances.

#### DISCUSSION

Since bone is an heterogenous or anisotropic material (4, 5, 6, 7), the laws that are applied to homogenous materials should be used with caution if at all. We have used standard formulae for our calculations for the sole purpose of comparing the effects of the various factors cited, but with the complete understanding that the values obtained may

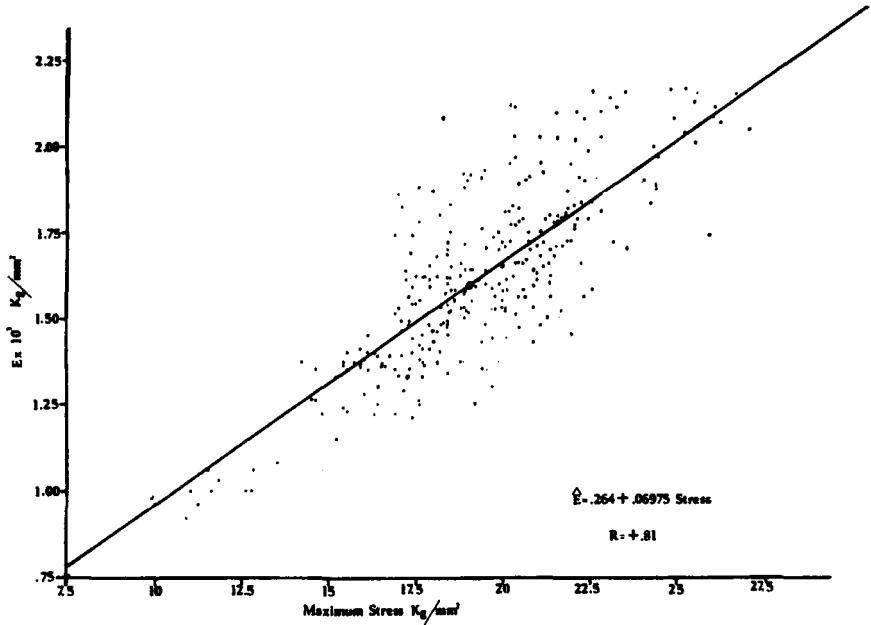


Figure 3. A scatter diagram depicting the relation between maximum stress and the modulus of elasticity in 318 wet tested specimens that were end-supported and centrally loaded at a rate of 1 cm/minute until failure. The line is the least squares best fit to the data for the estimate of modulus of Elasticity from maximum stress. The grand mean for both variates is indicated by the circle. The standard error of the estimate for the modulus of elasticity is .15. For the estimation of maximum stress modulus of elasticity, the following equation could be used, where  $\hat{\sigma}$  = estimated maximum stress.

$$\hat{\sigma} = 4.0 + 9.45E.$$

The standard error of the estimate is 1.8 kg/mm<sup>2</sup>.

not indicate the true properties of bone. The formulae utilized are presented in Appendix 2.

With these considerations borne in mind, the data in Table 1 can be evaluated from the standpoint of comparison of subjects. These data represent the findings on specimens that were subjected to identical type of loading under identical conditions. It can be seen that there is no consistent pattern as regards age. The differences between individuals in maximum stress and modulus of elasticity are highly significant as are the differences between the findings in tension and bending. Energy values are of borderline significance. The differences between tension and bending values from the same subjects may in part be accounted

## Femoral bending stress—14 subjects

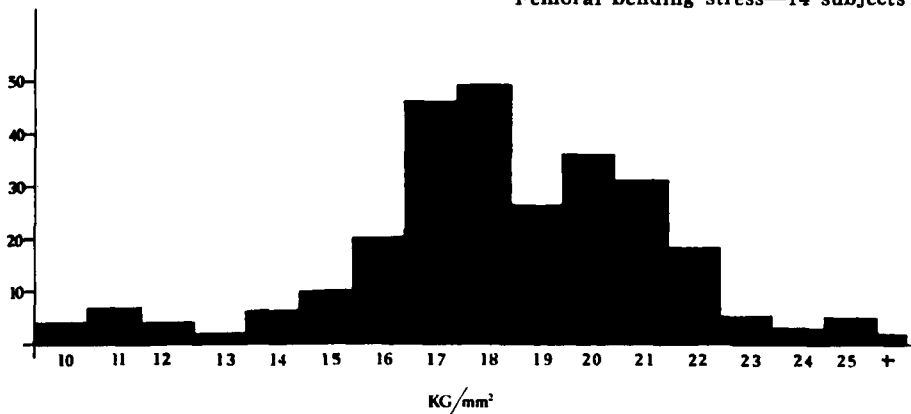


Figure 4. A Histogram showing the overall distribution of maximum stress in bending values in 14 subjects. It is felt that the relative decrease in the number of values at  $19 \pm .5$  kg/mm<sup>2</sup> is a chance occurrence due to the relatively few total number of subjects providing samples, and does not lessen the overall normal character of the distribution.

for by the difference in the rate of deformation of the specimens, but there is undoubtedly a real difference in the axis of loading that cannot be accounted for by rate.

In the bending specimens that were tested wet, a high correlation was present between the maximum stress and modulus of elasticity ( $R = +.81$ ;  $P < .001$ ) (Figure 3). An even higher correlation was noted when average values for subjects were compared. ( $R = +.95$ ;  $.01 > P > .001$ ). A similar comparison of the findings in the tension specimens demonstrated a much lower correlation ( $R = +.27$ ;  $.10 > P > .05$ ) in the individual samples. Thus, in bending, one can estimate one property if the other is known, and the appropriate equations are presented in Figure 3. This finding is in agreement with data for rat bone reported by *Weir et al.* (22). The overall distribution of physical properties in this group of adult human femoral samples is of the normal slightly skewed type as is seen in Figure 4.

Certain statistical problems are present in the comparative type of experiments that were performed. These have as their basis, the heterogeneity of bone, so that some variation in the properties is found if specimens are made from sites as close as 1 mm from each other. Thus, if one wished to determine the effect of one or another variate upon the ultimate strength of samples, a small real difference in results might not be of statistical significance unless an inordinate number of com-

parisons are made. This problem, can be circumvented in part, by performing tests and determining properties that enable one to use the same specimens several times, but it cannot be eliminated completely.

#### SUMMARY AND CONCLUSIONS

1. Values for physical properties calculated utilizing standard formulae were used as a basis of comparison of specimens that were prepared and loaded in identical fashion.

2. More than 500 specimens from mid-femoral diaphysis from 20 subjects were tested either in bending, tension, or compression.

3. It was found that:

a) There was no significant effect of temperature on maximum stress and energy absorbed to failure in the range between 21° C and 37° C. The modulus of elasticity may be slightly increased. Total deflection to failure is increased at 37° C.

b) Air drying alters the physical properties in less than one hour in the majority of instances.

c) Freezing of specimens prior to testing increases the strength of specimens insignificantly, but does not change any other property.

d) Fixation in formalin does not appear to alter the modulus of elasticity of small samples.

e) There is no difference in physical properties that can be attributed to size of specimen in the size ranges tested.

f) When bending bone as a beam with central load and unfixed end supports, the modulus of elasticity can be significantly changed by varying the distance between supports.

g) The cross-section dimensions of specimens should be measured before testing whenever possible.

h) Repeated loading of the same specimen does not alter the modulus of elasticity if loads of the order of 35 per cent of the breaking strength are used and one minute or more is allowed for recovery.

i) Specimens obtained from the lateral quadrant of the midfemoral diaphysis are stronger and those from the posterior quadrant are weaker with anterior and medial quadrants intermediate on average.

j) Determination of the volume of Haversian Canals in the specimen does *not* account for the bulk of the variation in the physical properties in individual specimens.

k) Significant differences exist in the physical properties of bone from different individuals that are not accounted for by age.

1) A high correlation is present between the maximum stress in bending and the modulus of elasticity in bending.

4. Bending tests of small samples of cortical bone appear to be reliable in the demonstration of differences in physical properties between individuals.

#### ACKNOWLEDGEMENTS

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#### RESUME

1. Il a été utilisé une formule standard pour calculer les valeurs des propriétés physiques comme base de comparaison pour des spécimens préparés et chargés de manière identique.

2. Plus de 500 spécimens de la diaphyse mi-fémorale provenant de 20 sujets ont été soumis à des épreuves de flexion, tension ou compression.

3. Il a été prouvé que:

a) la température n'a pas d'effet apparent en cas d'effort maximum et d'énergie absorbée jusqu'à limite de rupture dans l'intervalle entre 21 et 37° C. Le module d'élasticité peut s'accroître légèrement. La déflexion totale jusqu'à limite de rupture est accrue à 37° C.

b) La sécheresse de l'air altère les propriétés physiques en moins d'une heure dans la majorité des cas.

c) La congélation des spécimens avant l'épreuve accroît la force des spécimens d'une manière insignifiante, mais ne modifie aucune autre propriété.

d) La fixation dans la formaline ne semble pas altérer le module de l'élasticité des petits échantillons.

e) Il n'y a pas différence dans les propriétés physiques qui puisse être attribuée à la dimension des spécimens dans la rangée des dimensions mises à l'épreuve.

f) Lorsque l'os est ployé comme une poutre avec une charge centrale et des supports non fixés aux extrémités, le module de l'élasticité peut changer d'une manière sensible si l'on varie la distance entre les supports.

g) Les dimensions de la section en croix des spécimens doivent être mesurées avant l'épreuve lorsque cela est possible.

h) Une charge répétée sur le même spécimen n'altère pas le module de l'élasticité si des charges de l'ordre de 35 per cent de la force de rupture sont utilisées et qu'il s'écoule une minute ou plus pour récupérer entre les charges.

i) Les spécimens obtenus du quadrant latéral de la diaphyse mi-fémorale sont plus forts et ceux du quadrant postérieur sont plus faibles, les quadrants antérieur et médial étant dans la moyenne intermédiaire.

j) La détermination du volume des canaux de Havers dans le spécimen ne compte *pas* pour l'ensemble des variations des propriétés physiques des spécimens chez les différents sujets.

k) des différences sensibles qui ne sont pas dues à l'âge existent dans les propriétés physiques des os provenant de sujets différents.

l) Il existe une étroite corrélation entre l'effort maximum en flexion et le module de l'élasticité en flexion.

4. Les épreuves de flexion de petits échantillons d'os cortical semblent plus sûres pour la démonstration des différences des propriétés physiques chez les différents sujets.

#### ZUSAMMENFASSUNG

1. Werte für physikalische Eigenschaften, die mittels der Verwendung von Standardformeln errechnet waren, wurden als eine Vergleichsbasis von Proben, die in identischer Weise präpariert und belastet waren, gebraucht.

2. Mehr als 500 Proben der mittleren Femurdiaphyse von 20 Verstorbenen wurden entweder durch Beugung, Spannung oder Druck geprüft.

3. Es wurde gefunden dass

a) die Temperatur keinen entscheidenden Einfluss auf die maximale Belastungsfähigkeit oder auf die absorbierte Energie im Bereich zwischen 21 und 37° C. hat. Der Modulus der Elastizität mag leicht gesteigert sein. Das totale Biegungsvermögen bis zum Bruch ist bei 37° C. erhöht.

b) Lufttrocknung verändert die physikalischen Eigenschaften in weniger als einer Stunde in der Mehrzahl der Fälle.

c) Einfrieren der Proben vor der Prüfung vermehrt die Stärke der Probe unbedeutend, verändert aber keine andere Eigenschaft.

d) Fixierung in Formalin scheint den Elastizitätsmodulus von kleinen Proben nicht zu verändern.

e) Es besteht kein Unterschied von physikalischen Eigenschaften, welcher der Grösse der Proben in den geprüften Grössenbereichen zugeschrieben werden kann.

f) Wenn man Knochen wie einen Balken mit zentraler Belastung und beweglichen Endunterlagen biegt, dann kann der Elastizitätsmodulus mittels Verschiebung der Distanzen zwischen den Unterstützungspunkten bedeutend verändert werden.

g) Die Querschnittsgrössen von Proben sollten womöglich vor der Prüfung gemessen werden.

h) Wiederholte Belastung derselben Probe verändert nicht den Elastizitätsmodulus wenn eine Belastung die 35 Prozent der Brechungsstärke entspricht, verwendet wird und eine Minute oder mehr zwischen den Belastungen verstreichen darf.

i) Proben, die vom lateralen Quadranten der mittleren Femur Diaphyse erhalten werden sind stärker und die vom hinteren Quadranten sind schwächer, während die vorderen und medialen Quadranten dazwischenliegende Werte zeigen.

j) Bestimmung des Volumens der Haversschen Kanäle am Präparat gibt *keinen* Wertmesser für die Grösse der Variationen von physikalischen Eigenschaften der einzelnen Proben.

k) Der Knochen verschiedener Individuen weist bedeutsame Verschiedenheiten der physikalischen Eigenschaften auf, die nicht auf das Alter zurückzuführen sind.

l) Es besteht eine ausgesprochene Wechselwirkung zwischen der grössten Biegungsbelastung und dem Elastizitätsmodulus beim Biegen.

4. Biegungsprüfungen von kleinen Proben kortikalen Knochens scheinen verlässlich zu sein, um die Verschiedenheiten physikalischer Eigenschaften zwischen Individuen aufzuzeigen.

#### APPENDIX 1

##### *Definition of terms used in the text.*

**Force.**—Anything that tends to change a body with respect to its state of motion or the relative position of its molecular structure. The three basic types of forces are compression, tension, and shear (a push, a pull or a twist); all other forces representing these in combination.

**Stress.**—The intermolecular resistance within a body to force. It is a computed quantity expressed in psi., kg/mm<sup>2</sup>, or dynes/cm<sup>2</sup>. If the original cross-section area is utilized in the calculations, a value called the engineering stress is obtained. If the cross-section area during application of the load is used, the value is called the *true stress*. As indicated in the text, the dimensions determined during loading or after failure may be erroneous and in addition, there is real question concerning the

validity of the true stress concept. All calculations in this study are based on original cross-section dimensions.

**Strain.**—The forced change in dimensions or form of a body due to stress. A stretch is a tensile strain; a shortening is a compressive strain; an angular distortion is a shear strain. Commonly the term strain is used synonymously with the term *unit strain*, which is the elongation or shortening per unit length or change in angles between two lines originally at right angles to each other.

**Deformation.**—The term is used synonymously with strain here.

**Modulus of elasticity.**—The rate of change of unit stress with respect to unit strain for the condition of uniaxial stress within the proportional limit.

**Proportional limit.**—The greatest stress which a material can sustain without deviating from the law of stress-strain proportionality.

**Energy absorption.**—The work that is done per unit volume. In this report, the energy absorbed to failure or energy of rupture has been calculated.

**Moment of Inertia.**—A property of a plane area based upon its form that indicates its resistance to torque or bending forces.

**Isotropic.**—In this presentation, a material that has the same properties in all directions *i.e.* strength, modulus or elasticity.

**Strength.**—The limit to which a material can be strained. Here, it is used synonymously with the ultimate stress/unit area.

## APPENDIX 2

*Formulae used in calculation of the physical properties presented in the text.*

### Notation

$\sigma$ — Stress at failure	A — Cross-section area of specimen or test area
$\epsilon_u$ — Unit strain	B — Breadth of specimen
P — Load	D — Depth of specimen
I — Moment of Inertia	c — Distance from neutral axis of greatest fiber stress
E — Modulus of Elasticity	y — Maximum deflection in bending
$L_0$ — Original Length of Specimen or test area	
$L_1$ — Length of specimen at any point in loading	
M — Maximum Moment	

### Bending

$$M = \frac{PL_c}{4} \text{ (supported Beam)} \quad c = \frac{D}{2} \quad M = PL \text{ Cantilever}$$

$$\sigma = \frac{M}{I/c} = \frac{PL/4}{BD^3/12} \cdot X^2/D = \frac{3/2PL}{BD^3}$$

or as a cantilever

$$= \frac{PL}{BD^3/12X^2/D} = \frac{6PL}{BD^3}$$

$$E = \frac{PL^3}{48ly} \text{ or for a cantilever } \frac{PL^3}{3ly}$$

Tension

$$\sigma = P/A$$

$$E = \frac{P/A}{\epsilon_u} \text{ where } P \text{ and } \epsilon_u \text{ measured from most nearly linear portion of curve.}$$

Energy absorbed to failure is calculated from the area under a stress-strain curve utilizing a factor derived from the rate of deformation size of load, speed of recorder, and the volume of the specimen.

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