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## STUDIES ON SOME PHYSICAL PROPERTIES OF INFANT COMPACT BONE<sup>1</sup>

*By*

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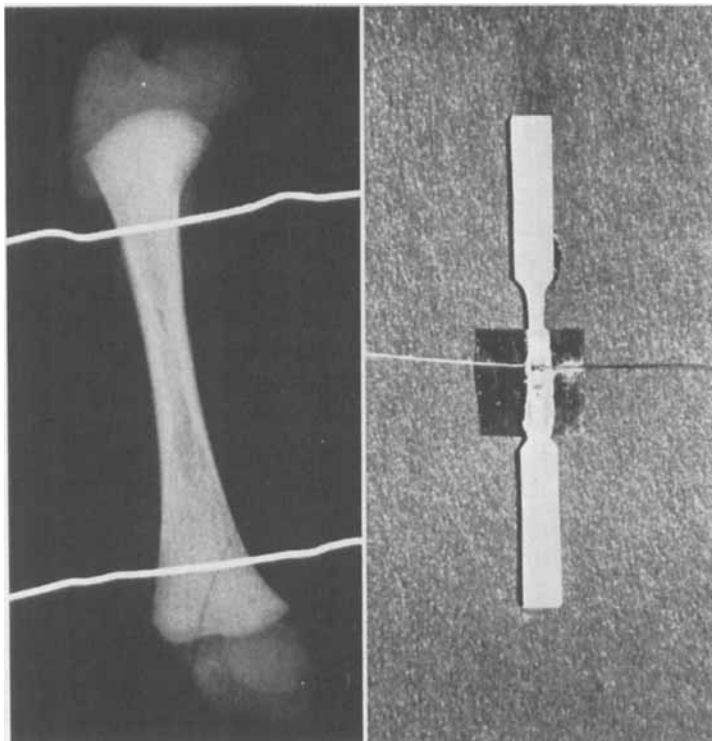
### INTRODUCTION

Tensile stress and strain of bone have been investigated less extensively than its other stress-strain characteristics. The probable reason for this is the technical difficulties involved in preparing and testing bone specimens in pure tension. The advantage of testing specimens in pure tension (or compression) is that the ultimate breaking stress (strength) of the specimen is much easier to calculate than when the specimen is tested in shearing or in bending.

When a specimen is tested under a pure stress (tension or compression) there is only one type of force involved and it is uniformly distributed over the cross sectional area of the specimen. Thus, the ultimate breaking stress of the specimen can be easily computed from the formula  $S = \frac{P}{A}$  in which S is stress, P is the breaking load and A is the cross sectional area of the specimen at the fracture site. When, on the other hand, a specimen is tested under bending its cross sectional area is subjected to a combination of tensile, compressive and shearing stresses which are not uniformly distributed over the cross sectional area of the specimen. Consequently, it is difficult to compute the ultimate breaking stress. Similar difficulties are encountered if a specimen is tested under shear. Diagrams showing the stress distribu-

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*Fig. 1.*

*Fig. 2.*

*Fig. 1.* Femur of a female 2 days old. The cortical bone available for making tensile test specimen is seen between the 2 markers.

*Fig. 2.* Tensile specimen with strain gage.

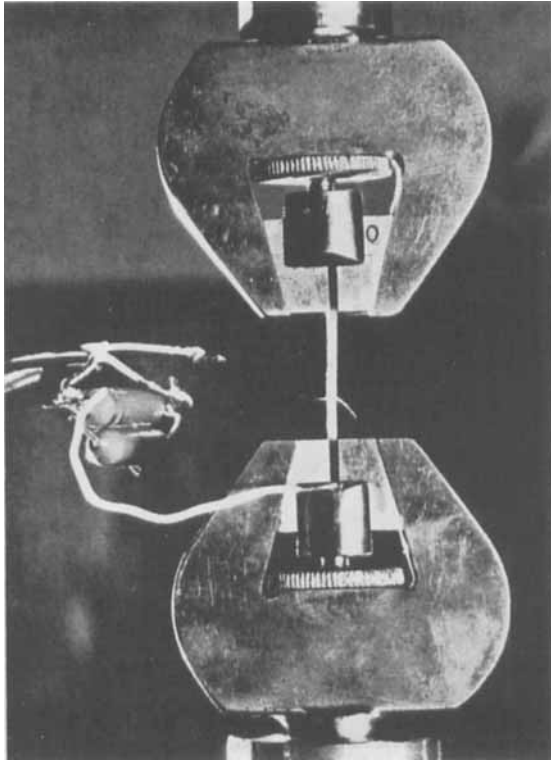
tion under the above conditions can be found in most textbooks on strength of materials.

#### MATERIALS AND METHODS

The material used in the present investigation was obtained from fresh autopsy limbs of infants and children of various ages. Because of the small size of the bones of infants, especially those of newborns, only the femur was large enough for our purpose. The autopsy limbs were kept separate in containers in a deep freezer at  $-20^{\circ}\text{C}$  until the test specimens were made.

At first small spindles, similar to those used by *Taysum, Evans et al.* (1962) in their study on some physical properties of tibias of irradiated beagle dogs, were tried. However, because of the small amount of cortical bone in the femurs of infants (Fig. 1), these had to be abandoned in favor of flat specimens. Flat test specimens are also much easier to make than spindles.

The specimens used in the present study were standardized as to shape (Fig. 2)

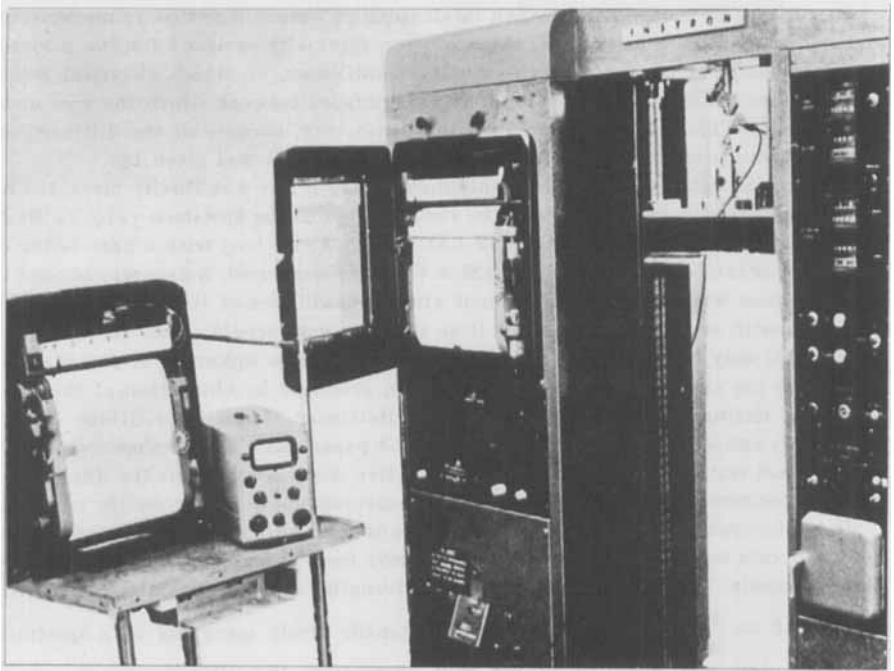


*Fig. 3.*

Close up view of jaws and specimen ready for testing. The object at the left is the lead from the strain gage to the recording bridge.

but their size varied with the amount of cortical bone available. The minimal size specimen successfully tested, especially if tensile strain was also determined, was approximately 25 mm long (with a reduced middle region 5 mm long and 1.3 mm wide), 1 mm thick and 3-4 mm wide at the gripping ends. The long axis of the specimen coincided with that of the intact bone. Reducing the cross sectional area of the middle part of the specimen concentrates the stress in that area where the tensile strain was also measured. A factor limiting the size of the specimen was the necessity that it be absolutely straight to ensure that the tensile force applied to it during a test was uniformly distributed over the cross sectional area of the specimen. In preparing the specimens care was taken to make as large a radius of curvature as possible at the fillet (junction between the reduced and non-reduced parts) to minimize the stress concentration in that region.

After the specimens were made they were put into separate vials and returned to the deep freezer. Shortly before testing the specimens were removed from the freezer and allowed to thaw so that they would be moist when tested. Preventing the specimens from drying is important because *Wertheim (1847), Rauber*



*Fig. 4.*  
Testing and recording apparatus.

(1876), *Hulsen* (1896), *Evans & Lebow* (1951), *Dempster & Liddicoat* (1952), *Lease & Evans* (1959), *Dempster & Coleman* (1961), *Evans* (in press) and *Sedlin & Hirsch* (in press) have all shown that drying affects the physical properties of bone.

Because of the thinness of the specimens (1 mm or less) great difficulty was encountered in holding them so they would not slip when loaded in the testing machine. The moist condition of the specimens also made them more difficult to hold. The kind of jaws used in earlier studies of the tensile strength of specimens from the long bones of adults (*Evans & Lebow* 1951) were not satisfactory for such small specimens so new jaws had to be designed. These jaws (Fig. 3) consisted of two wedge-shaped chucks, with rough faces and a thumb screw to exert additional force on the chucks and thus tighten their grip on the expanded ends of the specimens. The thumb screws also aided in aligning the specimens properly in the jaws.

The specimens were loaded to failure, under direct tension, in an Instron Tensile Testing Instrument, Model TT-BM (Fig. 4), calibrated to an accuracy of  $\pm 1$  per cent. The specimens were loaded in the direction of their long axis at a constant speed of 0.1 cm/min. and at a room temperature of 20–22° C and a humidity of 65 per cent. When mounting the specimen in the testing machine great care was taken to have the long axis of the specimen in perfect vertical alignment with the adapter holding the jaws in the Instron machine. This was necessary so that the tensile force would be uniformly distributed over the cross section area of the specimen when it was tested.

Attempts were made at first, when small spindles were being tried, to measure the tensile strain with a mechanical extensometer, especially designed for the purpose. The extensometer consisted of two flexible cantilevers, on which electrical strain gauges were bonded and pieces of safety razor blades between which the specimens were placed. This method proved to be unsatisfactory, because of the difficulty of properly attaching the extensometer to the specimen and was given up.

The tensile strain occurring in a specimen during a test was finally measured by cementing a strain gage directly to the reduced area of the specimen (Fig. 2). Budd Metafilm Foil Strain Gages (Type C12-LXL-M50A) 3 mm long with a gage factor of  $2.01 \pm 1$  per cent and a resistance of  $120 \pm 0.5$  ohms were used. A gage was bonded to the specimen with Eastman 910 cement after a small area of its surface had been swabbed with ether in order to dry it so that the gage would stick. The extent to which this may have influenced the results of the test is unknown at present. The change in the electrical resistance of the gage, produced by elongation of the bone specimen during a test, was recorded by a Hottinger Strain Gage Bridge (Model KWS/T-5) and a Speedomax recorder (Fig. 4). A paper speed of 30 cm/min. was used. Before each test the bridge was calibrated in five steps. After a test the dimensions of the specimen at the fracture site were measured under a microscope equipped with a micrometer ocular. Two measurements of the width and thickness were made and the cross sectional area computed (in  $\text{mm}^2$ ) from the average value of the two measurements. The ultimate tensile stress (strength) was then calculated from the formula  $S = \frac{P}{A}$  discussed previously. The tensile strain occurring in a specimen during a test was recorded as per cent elongation, the ultimate tensile stress (strength) in  $\text{kg}/\text{mm}^2$ .

During a test two curves—one for load (stress) and a second one for strain were automatically drawn on separate papers. From these curves the tangent modulus of elasticity of a specimen, which is a measure of its stiffness, was computed in  $\text{kg}/\text{mm}^2$ .

In this study bone is being treated as a material rather than as a structural unit. The conditions under which the specimens were tested have been deliberately simplified by comparison with those that would be expected for bone in a living body.

## RESULTS

The results of the tests can be divided into two groups—infant and child—on the basis of the age of the individual from whom the specimens were obtained. The specimens in the “infant” group came from individuals ranging up to six months of age while those in the “child” group were all from a fourteen year old boy. The values for the physical properties determined for these specimens as well as data on the individuals from whom the specimen came are given in Table 1.

A tendency toward an increase in ultimate tensile stress (strength) with the advancing age of the individual was noted with a rather marked separation between the strength values for specimens in the two groups.

TABLE 1  
Tensile Stress, Strain and Modulus of Elasticity of Compact Bone of Infants and Children.

Bone and specimen	Break area (mm <sup>2</sup> )	Breaking load (kg)	Ultimate tensile stress (kg/mm <sup>2</sup> )	Tensile strain (% elongation)	Tangent modulus of elast. (kg/mm <sup>2</sup> )	Specimen data
Femur 22-1	1.14	15.00	13.16	1.90	1281	Newborn. Female.
Femur 23-1	1.68	16.50	9.82	2.20	903	1 day old, male.
Femur 23-2	1.65	14.50	8.79	2.00	709	
Femur 3-1	1.54	14.50	9.42	0.50	1701	1 day old, female.
Femur 7-1	2.20	12.50	5.68	1.00	739	2 day old, male.
Femur 20-1	1.97	19.50	9.90	3.18	800	2 day old, sex?
Femur 9-1	1.45	16.50	11.38			1 week old, female.
Femur 9-2	1.36	16.00	11.76	1.60	1314	
Femur 21-1	1.73	10.50	6.07	1.00	803	2 month 5 day old, male.
Femur 10-1	1.30	15.25	11.73	2.31	908	6 month old, sex?
Femur 10-2	1.46	16.50	11.30	1.76	1164	
Femur 10-3	1.48	16.25	10.98	2.90	820	
Femur 12-1	1.30	22.00	16.92	1.86	1454	
Femur 12-2	1.37	28.00	20.44	1.72	2273	
Femur 12-3	1.22	22.50	18.44	1.41	3251	
Femur 12-4	1.70	25.00	14.70	2.68	2000	14 year old, male.

The latter was evident from a comparison of the average tensile stress which was 10.00 kg/mm<sup>2</sup> for the specimens in the infant group and 17.625 kg/mm<sup>2</sup> for specimens from the 14 year old boy.

The tensile strain (per cent elongation) did not exhibit any consistent trend and there was only a slight difference between the average tensile strain for the specimens from the infant (1.850 per cent elongation) and the child (1.918 per cent elongation) group.

The modulus of elasticity was generally higher in specimens from older than from younger infants but this was not consistently true. However, the modulus of every specimen from the fourteen year old boy was higher than that of any specimen in the infant group. The average modulus was 1012.9 kg/mm<sup>2</sup> and 2244 kg/mm<sup>2</sup> for the specimens from the infants and the boy, respectively.

For some unexplainable reason the ultimate tensile stress and modulus of elasticity of the only specimen from a newborn (specimen No. 22-1) were much higher than any of the other infant specimens.

#### DISCUSSION

Before discussing the results of the tests certain technical factors which may have influenced the values obtained for the various physical properties studied will be briefly discussed. The effect of these factors is primarily because of the small size of the test specimens. Thus, because of the thinness of the specimens (approximately 1 mm), the evaporation of the ether used to dry the area to which the strain gage was attached or any other drying of the specimen that occurred during the few minutes required to test it would affect its physical properties more than would be true for larger specimens from adult bones. The values obtained for the physical properties of the specimens would also be influenced by the tensile strength (stress) of the strain gage itself and of the Eastman 910 cement used for attaching the gage to the specimen. However, the Budd Metafilm strain gage, according to information supplied by the manufacturer, consists of a thin piece of foil (0.000254 cm thick) overlying a layer of epoxy (0.00381 cm thick). It is very unlikely that the strain values obtained for the specimen, upon which the gage was placed, would be affected by the gage itself because the modulus of elasticity of the epoxy (351.1 kg/mm<sup>2</sup>) is far less than that ever reported for compact bone.

The heat generated during the machining or other procedures used in making test specimens may also produce some changes in the physi-

cal properties of the bone unless special precautions are taken to dissipate the heat. The effect of stress concentration produced by spaces within the bone is also greater in specimens with a small cross sectional area than in those with a larger cross sectional area. The effects of these factors on the physical properties of bone are now being studied. When sufficient data have been obtained they will be analyzed to determine if any of the effects found are of statistical significance.

Because of the small amount of cortical bone in the shaft of the femur of an infant it was very difficult to prepare test specimens that consisted entirely of compact bone. In several specimens the reduced area might be entirely cortical bone while the expanded gripping ends of the specimen would be a mixture of compact and spongy bone. In some specimens one side would be more or less compact bone but the other side would have a considerable amount of spongy bone. Areas of spongy bone at the ends of the specimen would crush easily and thus make the specimen more difficult to grip. If there was spongy bone in the reduced region of the specimen, where the strain was measured, it would make it very difficult to obtain proper attachment of the strain gage to the specimen.

The small amount of strain (Table 1) in specimens from femurs 3, 7 and 21 was probably due to faulty attachment of the strain gage as one side of the reduced area in these specimens consisted of quite a lot of spongy bone. No strain record was obtained from specimen 1 of femur 9 because the strain gage was not tightly fastened to the bone. The probable reason for this is that the specimen was tested too soon after mounting of the strain gage and the Eastman 910 cement, with which the gage was attached to the bone, had not had time to dry thoroughly.

A small amount of stress, probably because of irregularities in the surface of the expanded gripping ends of the specimen, was applied to the specimen during its mounting in the jaws of the testing machine. This stress was allowed to disappear, which occurred in a very short time, before the test was started.

The specimen containing some spongy bone might tend to dry out more during testing than would a similar specimen of compact bone. Such a tendency to dry would probably affect the results of a test because drying increases the tensile strength (*Wertheim 1847, Rauber 1876, Hulsen 1896, Evans & Lebow 1951, Dempster & Liddicoat 1952*), compressive strength (*Rauber, loc.cit., Dempster & Liddicoat, loc.cit.*), bending strength (*Dempster & Coleman 1961*), modulus of elasticity (*Rauber, loc.cit., Evans & Lebow, loc.cit., Dempster & Liddicoat, loc.cit.*)

and hardness (*Evans & Lebow*, loc.cit.) of human compact bone. *Lease & Evans* (1959) found that the fatigue strength of intact metatarsals from embalmed adult human cadavers is decreased by drying. This is also true for the energy absorbing capacity and shearing strength of standardized specimens of compact femoral bone from embalmed cadavers (*Evans & Lebow*, loc.cit.).

As far as the authors know there have been no previous studies on the physical properties of infant long bones. Nevertheless, it is instructive to compare our results with those obtained by others who have determined the corresponding physical properties in specimens from adult long bones. Direct comparisons are difficult because of differences in the methods of testing the specimens, differences in the condition of the specimens, differences in the predominate orientation of the collagen fibers in the specimen with respect to the direction of loading and lack of information about the age, sex, race, state of health or cause of death of the individual from whom the specimens were taken. The latter are factors over which the investigator has little control, especially with respect to human bone, but any or all of them may influence the results of the tests. The bone and region of the bone from which the specimens were taken should also be considered when comparing results reported by various investigators (see ref.) because there are statistically significant differences in some of the physical properties of specimens from different bones or from corresponding regions of the same bone (*Evans*—in press).

Comparison of the average and range of variation in the physical properties of our specimens and similar data obtained by others for compact bone from the femurs of adults is presented in Table 2. The original stress and modulus data of *Carothers, Smith & Calabrisi* (1949), *Evans & Lebow* (loc.cit.) and *Evans* (unpublished) were given in terms of lbs/in<sup>2</sup> but have been converted into kg/mm<sup>2</sup> for comparison with our data and those of *Wertheim* (loc.cit.) and *Rauber* (loc.cit.).

Examination of the data in Table 2 shows that the average ultimate tensile strength (stress) for our specimens from infants was greater than that for moist fresh and wet embalmed specimens from adult femurs. Only dry tested embalmed specimens from adult femurs had a greater average tensile strength and even these were less than our value for fresh moist tested specimens from a 14 year old boy. The range of variation in the tensile strength of our specimens from infant femurs was similar to that reported by *Rauber* for fresh specimens from adult bones. However, the maximum tensile strength of the specimens from

TABLE 2  
*Average and Range of Variation of Some Physical Properties of Young and Adult Human Compact Bone.  
 The Load was in the Direction of the Long Axis of the Specimen and the Intact Bone.*

Author	Specimen source	Specimen condition	Ultimate tensile stress (kg/mm <sup>2</sup> )	Ultimate tensile strain (% elongation)	Tangent modulus of elast. in tension (kg/mm <sup>2</sup> )
Hirsch, Evans	Infant femur Newborn—6 mo. old 12 specimens	Fresh	10.00	1.850	1012.9
		Moist	(5.68-13.16)	(1.60-3.18)	(709-1281)
	14 yr. old boy 4 specimens	Fresh	17.625	1.918	2244.5
		Moist	(14.70-20.44)	(1.41-2.68)	(1454-3251)
Wertheim 1847	Adult femur 4 specimens	Fresh	7.765		2264.7
		Moist	(6.397-10.496)		(1819-2638)
Rauber 1876	Adult femur 24 specimens	Fresh	9.029		2245.5-14 spec.
		Moist	(5.743-13.245)		(1891-2560)
Carothers, Smith and Calabrisi 1949	Adult femur 10 specimens	Dry	15.466		
		Embalmed	(11.6698-22.145)		
Evans and Lebow 1951	Adult femur 121 specimens Male	Wet	8.324	1.20	1595.8
		Embalmed	(4.914-10.897)	(0.56-2.55)	(787.4-2151.2)
		Dry	10.776	0.66	1877.0
		Embalmed	(6.144-15.123)	(0.29-1.13)	(1202.1-2580.0)
Evans Unpublished	Adult femur 70 specimens Female	Wet Embalmed	7.387	1.740	1330.2

infants was less than that of similar specimens from dry embalmed adult bones.

The average tensile strain (per cent elongation) of our specimens was also greater than that of wet and dry tested embalmed specimens from adult femurs. However, their range of variation was less than that of embalmed wet tested specimens from adults. *Wertheim's* tensile strain values were omitted from Table 2 because of some uncertainty of the accuracy of his values and *Rauber's* because he determined his strain values under bending during which the specimens are subjected to a combination of tensile, compressive and shearing forces. *Carothers, Smith & Calabrisi* did not determine strain in their specimens.

In comparing our results for tensile stress with those of others, it should be remembered that *Wertheim* used long strips of bone, instead of tensile specimen similar to ours, and that he reported great difficulty in holding his specimens for testing. The specimens tested by *Evans & Lebow* (loc.cit.), *Evans* (1957) and *Evans* (unpublished) were from embalmed rather than fresh bone and it has been shown that embalming significantly increases (1 per cent level of significance or better) the ultimate tensile strength of human compact bone (*Evans*, in press). Another factor to be considered is that the specimens tested by *Carothers, Smith & Calabrisi* were from the proximal part of the femoral shaft, a region whose tensile strength is significantly less than that of other areas of the shaft (*Evans*, in press).

In comparing our results for per cent elongation with those obtained by other investigators it should be remembered that *Evans & Lebow* (loc. cit.) found that drying decreases the tensile strain in human compact bone.

The most interesting result of our study is the demonstration that the average and range of variation in the tangent modulus of elasticity of compact bone from infant femurs is considerably less than that of adult femoral compacta.

#### SUMMARY AND CONCLUSIONS

1. A method is described for determining the ultimate tensile stress (strength), tensile strain (per cent elongation) and tangent modulus of elasticity of miniature specimens of compact bone from the femurs of infants (newborn—6 months of age) and a 14 year old boy.

2. The average ultimate tensile stress of specimens from infants was greater than that reported by other investigators for fresh specimens from adult femurs. The range of variation in the tensile stress of the

specimens from infants was similar to *Rauber's* results for fresh specimens from adult bones. The average ultimate tensile stress of specimens from the femur of a 14 year old boy was greater than that of any specimens of adult bone regardless of the test condition of the latter (fresh or embalmed, wet or dry).

3. The average tensile strain of specimens from infant femurs is greater than that for fresh specimens from adult bones. However, specimens from infants have less range of variation in tensile strain.

4. The average and range of variation in the tangent modulus of elasticity of specimens from infants is considerably less than that of similar specimens from adult bones.

5. A survey of available literature revealed no previous studies of the ultimate tensile stress, tensile strain and tangent modulus of elasticity of compact bone from infants.

#### RESUME

1. Il est décrit une méthode pour déterminer la résistance à la tension, la force de la tension (en pour cent d'élongation) et le module tangent d'élasticité de spécimens miniature d'os compact provenant de fémurs d'enfants (nouveaux-né jusqu'à 6 mois) et d'un garçon de 14 ans.

2. La résistance moyenne à la tension pour les spécimens provenant d'enfants s'est montrée plus élevée que celle rapportée par d'autres chercheurs pour les spécimens frais de fémurs d'adultes. La gamme des variations de la résistance à la tension pour spécimens provenant d'enfants était similaire aux résultats de Rauber pour les spécimens frais d'os d'adultes. La résistance à la tension pour les spécimens du fémur d'un garçon âgé de 14 ans était plus élevée que celle d'aucun autre spécimen d'os adulte, sous quelle forme qu'il ait: frais ou conservé, humide ou sec.

3. La force moyenne de la tension pour les spécimens de fémurs d'enfant est plus forte que pour les spécimens frais d'os adultes. De toute manière, les spécimens provenant d'enfants montrent moins de variations dans la force de la tension.

4. La moyenne et la gamme des variations du module tangent d'élasticité de spécimens provenant d'enfants sont moins élevées que celles de spécimens similaires d'os adultes.

5. Un examen de la littérature dont on dispose n'a pas révélé d'études antérieures sur la résistance à la tension, la force à la tension et le module tangent d'élasticité d'os compact provenant d'enfants.

## ZUSAMMENFASSUNG

1. Eine Methode zur Bestimmung der äussersten Dehnungsbeanspruchung (Stärke), der Dehnungsspannung (Prozent Verlängerung) und der tangentialen Grösse der Elastizität von kleinsten Proben des kompakten Knochens des Femurs von Kindern (Neugeborenen – 6 Monate alten) und von einem 14 jährigen Knaben wird beschrieben.

2. Die durchschnittlich grösste Dehnungsbeanspruchung der Proben von Kindern war grösser als die, welche von anderen Untersuchern für frische Proben von Femuren Erwachsener berichtet wurde. Die Variationsbreite der Dehnungsbeanspruchung von kindlichen Proben glich den Ergebnissen Raubers für frische Proben von Knochen Erwachsener. Die durchschnittlich grösste Dehnungsbeanspruchung von Proben des Femurs eines 14 jährigen Knaben war grösser als die irgendwelcher Proben des Knochens Erwachsener ohne Rücksicht auf den Prüfungszustand des letzteren (frisch oder aufbewahrt, nass oder trocken).

3. Die durchschnittliche Dehnungsspannung von Proben kindlicher Femuren ist grösser als die von frischen Proben der Knochen Erwachsener. Proben von Kindern habe jedoch eine geringer Variationsbreite der Dehnungsspannung.

4. Der Durchschnitt und die Variationsbreite des tangentialen Masses der Elastizität von kindlichen Proben sind bedeutend geringer als die von entsprechenden Proben der Knochen Erwachsener.

5. Eine Durchsicht der erhältlichen Litteratur wies keine früheren Untersuchungen über die Dehnungsbeanspruchung, die Dehnungsspannung und das tangentielle Mass der Elastizität von kindlichem kompaktem Knochen auf.

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