

MECHANICAL PROPERTIES OF DRIED DEFATTED SPONGY BONE

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A study has been made of the compressive strength, compression at rupture, limit of proportionality, compression at the limit of proportionality and the modulus of elasticity of spongy bone from vertebrae and tibias. The specimens were obtained from autopsy subjects of both sexes aged 14 to 89 years. There was a qualitative deterioration of most of the strength parameters with age, and also differences between the sexes and between vertebrae and tibia. Spongy bone was found to have the unusual mechanical property that, despite rupture, its compressive strength often steadily increased; this was especially the case for vertebrae from young males.

Key words: mechanical properties; spongy bone; apparent density; compressive strength; osteoporosis; age changes

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The mechanical properties of spongy bone have received little attention in the literature. Evans (1957) gives only one reference, viz. Rauber (1876), who reported the respective compressive strengths for spongy bone from vertebrae and femoral condyles as 0.84 and 0.96 kgf/mm² for two groups, each of four specimens, with a range of about 20 per cent. This examination of the mechanical properties of spongy bone has been carried out with special reference to any variations associated with age and sex.

MATERIAL

Spongy bone was obtained from the lowermost two to four lumbar vertebrae, and from the head of the tibia in 60 autopsy subjects. In general, specimens were taken from four men and four women in each age decade between

14 and 89 years. The material has been described in detail elsewhere (Lindahl 1962); it has also been used for an examination of the degree of osteoporosis, which was determined by measuring the apparent density of spongy bone.

METHODS

Fresh spongy bone was sawn into cubes measuring about 2×2×4 cm. These were cleaned of blood and fat by repeated flushing with hot water and then leached in water for 48 hours; after drying, any remaining fat was removed with xylol, and the cubes were then dried again and stored in air at 3-5° C. Before the mechanical tests the specimens were conditioned for 2 months at 65 ± 3 per cent relative humidity and 20 ± 1.0° C. From the specimens accurately rectangular test bodies were sawn. The height in the axial direction of the pores was usually 10 mm, sometimes slightly less, and the base dimensions were 9-39 × 14-60 mm. The compressive tests were carried out at the National Testing Laboratory in an Alwetron testing

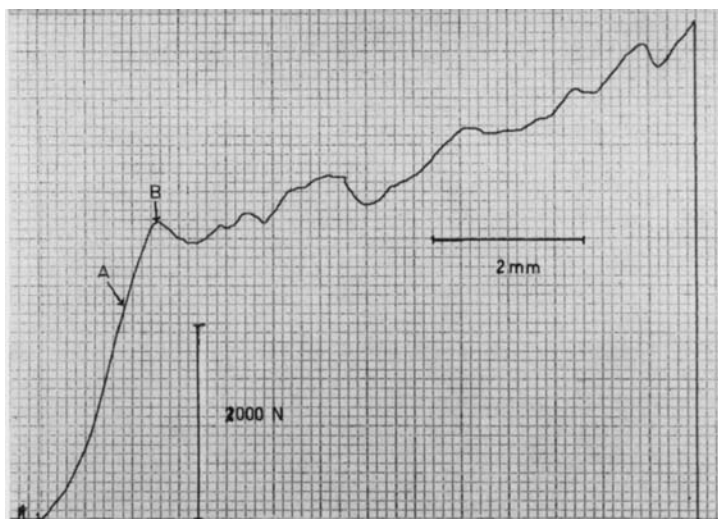


Figure 1. Stress/compression curve for spongy bone. Type I. A, The limit of proportionality between compressive force and deformation. B, Breaking point. The scales for the compressive force and deformation are entered on the curve.

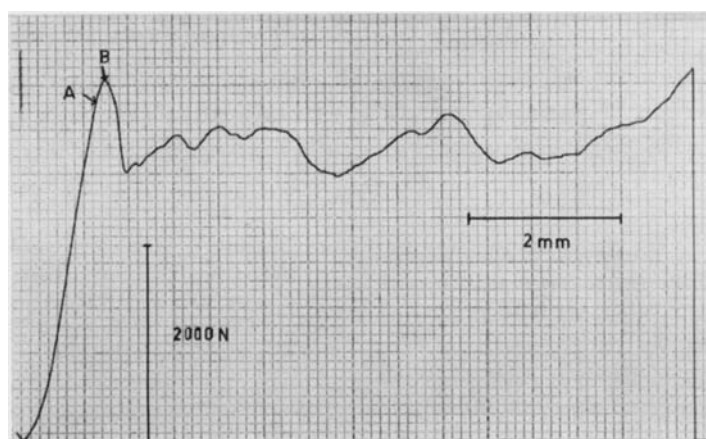


Figure 2. See Figure 1. Curve type E.

machine at a deformation rate of 0.05 mm/min. The compression in the axial direction was discontinued when the height of the test bodies had been reduced by two thirds. The strength parameters, including the compressive strength, limit of proportionality, compression at rupture and modulus of elasticity, were calculated as described in an earlier paper (Lindahl 1968).

Using these test bodies, compression at the limit of proportionality was also calculated. This is the percentage deformation of the original length of the body at the point where the proportionality of compression to applied force ceases (Point A, Figure 1).

For the mechanical properties of vertebrae, the values are recorded as the means of the values for test bodies from two to four lumbar vertebrae originating from the same subject.

The mean, standard deviation, standard error of the mean and coefficients of regression were calculated by the usual statistical methods (Snedecor & Cochran 1962).

RESULTS

The compression curves. Whereas the load/deformation curve obtained for

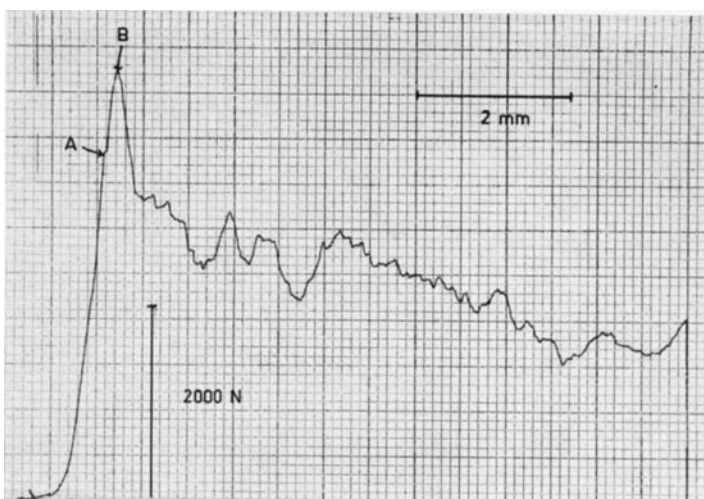


Figure 3. See Figure 1. Curve type D.

“conventional” material usually approximates closely to that for tensile strength tests, the load/deformation curves for spongy bone are atypical and variable. There is usually no difficulty in ascertaining the stress at which the material collapses but, unlike other substances, spongy bone usually undergoes no total loss of strength during rupture.

For this material it is possible to dis-

tinguish three main types of stress variation, viz.:

- (1) a steady increase until compression is discontinued, possibly after a small drop (type I; increase, Figure 1).
- (2) largely constant stress after rupture throughout the period of compression (type E; equal, Figure 2); and

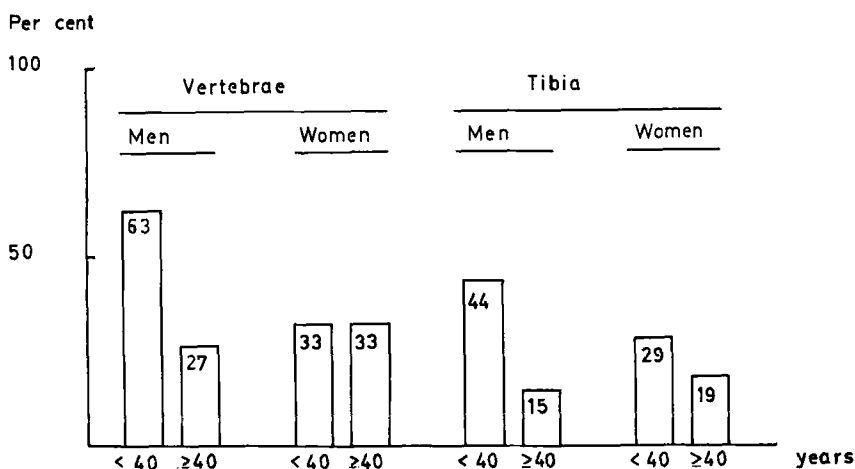


Figure 4. Percentage of type I curves for various groups (males, females; vertebrae, tibia) for ages (< 40 and ≥ 40).

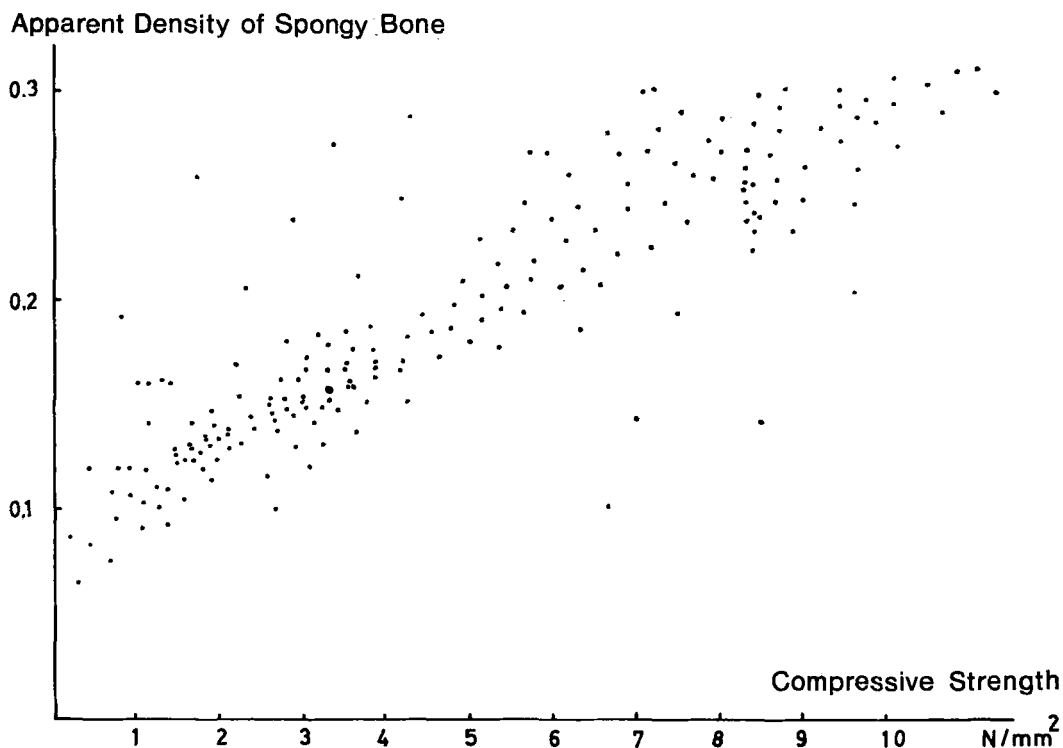


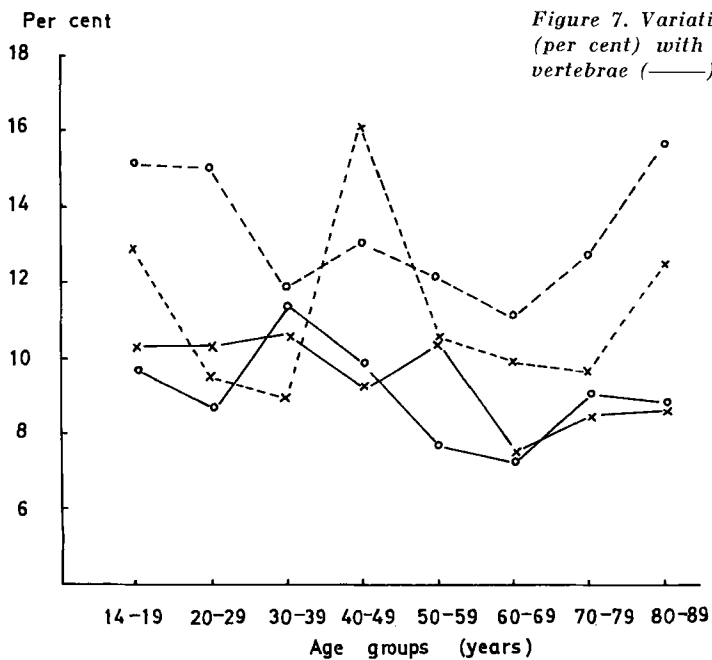
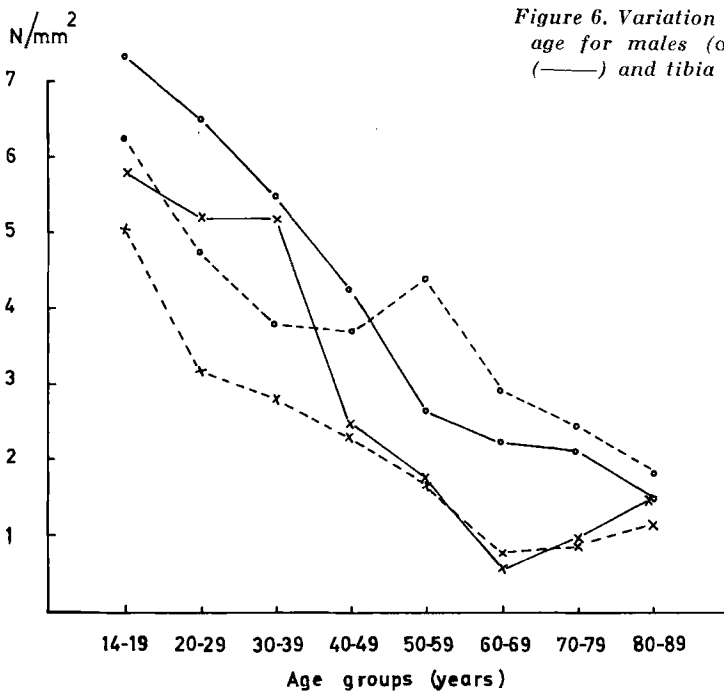
Figure 5. Relationship between apparent density and compressive strength of spongy bone. Each point relates to one specimen.

(3) after rupture a steady decrease in stress throughout compression (type D; decrease, Figure 3).

For 201 test bodies the distribution of types I, E and D was 38, 49 and 13 per cent, respectively; thus, type D was much less common than the other two. From the aspect of biological and mechanical properties the first type of stress variation (I) is evidently superior to the other two, for in spite of the rupture, the strength of the compressed bone increased steadily. Accordingly an examination was made of the distribution of this type of curve with respect to compressive strength, age and sex. No connection could be traced between strong bone (with a high compressive strength) and bone with a "favourable" type I curve. High and low strength were found

in combination with all three types of curves. There would seem to be tendency, however, for type I curves to be more common in the lower age groups, and more common in men than in women. From comparisons of the frequencies of such curves made for the age groups < 40 and ≥ 40 , for the two sexes and for vertebrae and tibia, presented in Figure 4, it is seen that they were more common in the lower age groups, in men rather than in women, and in vertebral rather than in tibial bone, and thus most common for vertebral specimens in young males. These differences are not statistically significant.

Relation between apparent density and compressive strength. In an earlier paper the author proposed that the apparent density (the weight per unit volume of bone, including cavities), which is equiv-



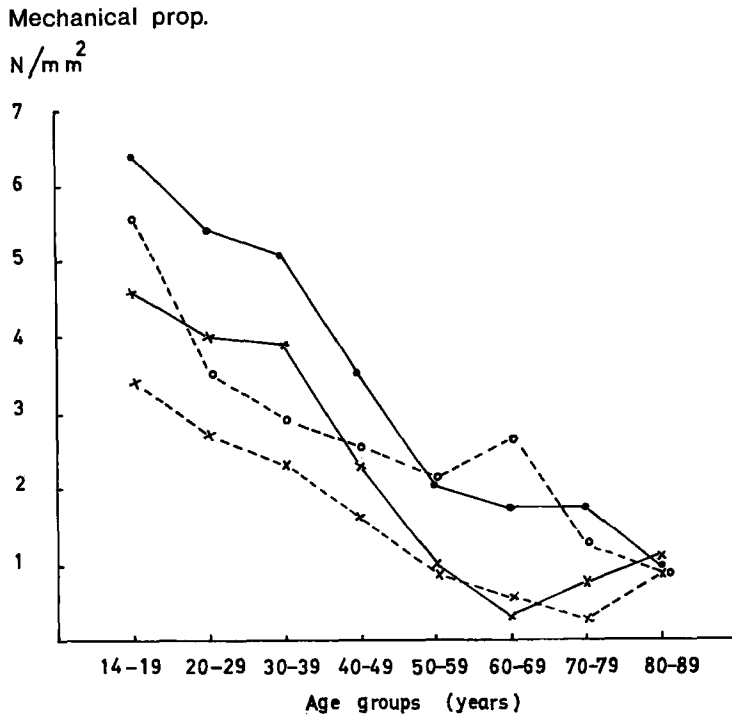


Figure 8. Variation of limit of proportionality with age. Males (o) and females (x); vertebrae (—) and tibia (---).

alent to the porosity, reliably represents the degree of osteoporosis of spongy bone (Lindahl 1962). The compressive strength would presumably be inversely dependent on the porosity. From the plot of compressive strength against apparent density for all 201 specimens (Figure 5) it is seen that there was a close correlation between these two parameters; this is statistically highly significant (***) with a correlation coefficient of 0.7.

Compressive strength. See Table 1. For both vertebrae and tibia there was a significant sex difference (**), the values being about 75 per cent higher for the men. Since there is a relationship between compressive strength and apparent density it is conceivable that this sex difference was due solely to differences in apparent density. When, however, the compressive strength was plotted against

the apparent density—giving what may be termed the “relative compressive strength”—the sex difference remained; this means that besides the lower compressive strength in women, due to greater porosity of the bone, there was also a qualitative difference. Spongy bone from the tibia and vertebrae in the same person did not differ in this respect. The compressive strength decreased with age in both sexes and for both tibia and vertebrae (Figure 6). Here, too, calculation of the “relative compressive strength” showed a reduction with age that was less pronounced but still significant (**); this is indicative of an age-dependent change in quality unrelated to the porosity; this decrease amounted to about 20 per cent.

Compression at rupture. See Table 1. The values were higher for the tibia than the vertebrae; the difference for the

Table 1. Mechanical properties of spongy bone.

	Males				Females			
	Vertebrae (n = 32)		Tibia (n = 32)		Vertebrae (n = 32)		Tibia (n = 32)	
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
Compressive strength N/mm ²	4.6	0.3 (0.2—10.5)	3.9	0.3 (0.2— 6.7)	2.7	0.2 (0.3— 7.0)	2.2	0.2 (0.6— 4.8)
Compression at rupture per cent	9.5	0.4 (5.3—14.4)	13.4	0.8 (4.1—26.8)	9.0	0.6 (3.2—14.7)	11.6	1.1 (3.8—25.8)
Limit of proportionality N/mm ²	4.0	0.1 (0.1— 9.7)	2.8	0.1 (0.1— 7.3)	2.2	0.1 (0.2— 6.0)	1.5	0.1 (0.1— 7.5)
Compression at the limit of proportionality per cent	6.7	0.2 (4.1— 8.6)	8.3	0.7 (3.7—18.9)	6.1	0.4 (2.6—10.0)	6.9	0.6 (1.4—14.3)
Modulus of elasticity N/mm ²	55.6	0.7 (1.1—139.1)	34.6	0.4 (2.5—74.4)	35.1	0.6 (5.2—103.6)	23.1	0.4 (1.4—79.2)

1 Newton/mm² (N/mm²) = 0.102 kilopond (kp) or kilogramme force/mm² (kgf/mm²) = 145 lb/in² (psi).

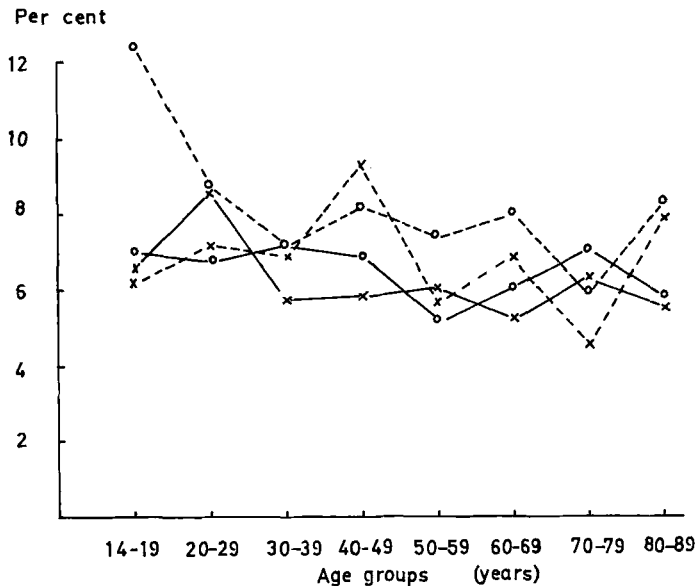


Figure 9. Variation of percentage compression at limit of proportionality (per cent) with age. Males (o) and females (x); vertebrae (—) and tibia (----).

males was 41 per cent and highly significant (***) , and for the females 29 per cent and not significant. There was no sex difference, nor any change with age (Figure 7).

Limit of proportionality. See Table 1. For both tibia and vertebrae the values were higher for men than women. The difference was about 90 per cent and highly significant (***) . The values were

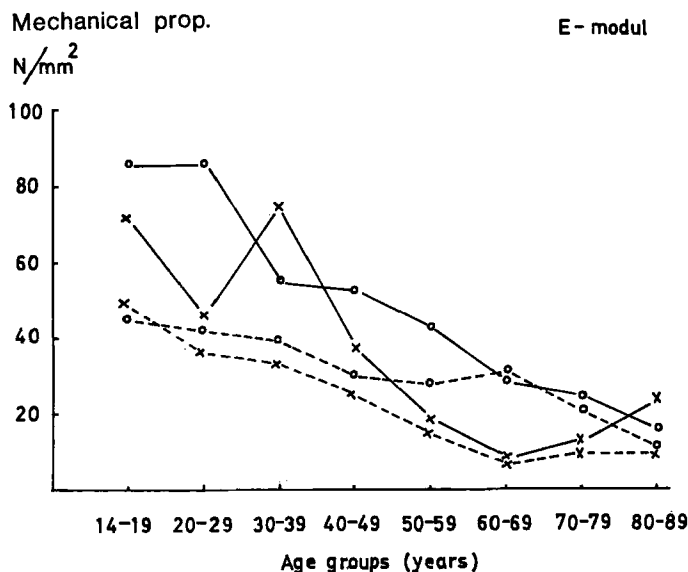


Figure 10. Variation of modulus of elasticity with age. Males (o) and females (x); vertebrae (—) and tibia (----).

higher for the vertebrae than for the tibia—also highly significant (***) . From the graph in Figure 8 it is seen that there was a marked and highly significant (***) reduction with age of the order of 90 per cent.

Compression at the limit of proportionality. See Table 1. The sex difference was fairly small. The values were highly significant (***) more so for the tibia than for the vertebrae. There was no significant reduction with age (Figure 9).

Modulus of elasticity. See Table 1. Comparison of the values for the vertebrae and tibia disclosed highly significant and higher (***) values for the vertebrae. The values for men were higher than for women, but not at the level of significance. There was a significant (**) reduction of 30 per cent with age (Figure 10).

DISCUSSION

One important benefit derived from this study is the complete set of data on

various strength parameters for spongy bone. Also of interest is the fact that, in spite of the rupture of spongy bone it retained, or in some cases even improved, its compressive strength. Just as for compact bone, most of the strength parameters examined decreased with age; exceptions were the compression at rupture and the limit of proportionality.

It might be wondered whether this impairment of quality with age might be due solely to a simultaneous lowering of the apparent density (resulting from an increase in porosity). Since, however, the reduction in the various strength parameters was considerably greater than the drop in apparent density, there must have been a direct change in quality as well as the increase in porosity with age. A corresponding reduction in strength with age has been demonstrated for compact bone (Lindahl 1968), and these two trends account in some measure for the greater tendency for fractures to occur at advanced age.

In addition, the compressive strength and limit of proportionality were greater

for men than women. The fact that these differences were larger than could be accounted for by the sex difference in apparent density also points to a difference in mechanical quality.

The difference between vertebrae and tibia is difficult to assess. The former had a higher modulus of elasticity and limit of proportionality, whereas the tibia had a higher percentage compression at rupture.

The reason for these differences might be disclosed by further research in the subject, but for the time being it must

suffice to ascribe them to adaption to a difference in the functional demands on the two bones.

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