

TORSIONAL STRENGTH AND GEOMETRY OF DIAPHYSEAL BONE

An Experimental Study on Dogs

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A previously presented method for measuring the torsional strength of diaphyseal bones has been used to study the effect of direction of twist upon the torsional strength and stiffness of diaphyseal canine bones. No significant effect of the direction of twist upon the studied properties has been found. The reason for the observed twist direction independence of the torsional strength and stiffness is assumed to be the adaptation of the diaphyseal bone architecture to functional demands.

Key words: bone; experimental measurement of bone stiffness; experimental measurement of bone strength; maximum torque capacity; strength properties

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The maximum torque capacity is considered a suitable measure of strength of diaphyseal bones (in the following referred to as long bones). Torsion testing has been used by previous investigators to study the strength of long bones themselves or the effect of different treatments upon their strength (Burstein & Frankel 1971, Burstein et al. 1972a, Sammarco et al. 1971, Uhtoff & Duboc 1971, Mensch et al. 1976, Strömberg & Dalén 1976a, b).

Previously, both bones of a pair have, with few exceptions, been twisted either inwardly or outwardly (Sammarco et al. 1971,

Strömberg & Dalén 1976), that is, the twist direction with respect to the bone geometry has been the same for both bones and the possible effect of the twist direction upon the torsional strength has been eliminated. Others have not stated the actual twist direction at the tests, obviously assuming this to have no effect upon the torsional strength (Burstein et al. 1972a, Mensch et al. 1976). Moreover, in the literature no report has been found where the effect of the anatomical asymmetry of bones upon their torsional strength has been studied. From the point of view of strength of materials nothing contradicts the assumption that the torsional strength of an asymmetric body depends upon the direction of twist.

The aim of this study is to elucidate the effect of the anatomical asymmetry of long bones upon their torsional strength and

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stiffness. The effect has been studied by twisting bones of a related pair in different directions with respect to the bone geometry at the torsional tests.

MATERIAL

The test material chosen was 7 related pairs of femora and 13 pairs of tibiae, with closed epiphyseal lines, from long legged dogs of both sexes and of varying breed. From each related pair of bones, one was selected at random for outward twist and the other for inward twist.

Preparation

The animals were sacrificed with lethal doses of mebumal-sodium (Nembutal[®], Abbott Laboratories, USA) administered i.v. Immediately after sacrifice the bones were freed of all soft tissue except the periosteum. The bones were wrapped in gauze saturated with physiological saline solution and inserted into plastic bags. After sealing, the bags were stored in a freezer at a temperature of -30°C . Prior to testing the bags were put into physiological saline solution at $+20^{\circ}\text{C}$ for 2 hours. Both bones of a related pair were always simultaneously frozen or thawed. The bones were taken from the saline solution only immediately prior to testing. The time interval between the tests of two related bones was in all cases less than 10 minutes.

TORSIONAL TESTING PROCEDURE

The bones were twisted to fracture in a special apparatus for torsional testing of long bones. Undue stress concentrations in the bones were prevented by using a previously described method for fixation of test bones in the twist machine grips (Strömberg & Dalén 1976a). During the test the torque-time relationship was plotted on a time base recorder (Hewlett-Packard 7005 B). The angular velocity of the torsion machine is constant and independent of torque in the test range. The torque-twist curve for a bone is thus readily obtained by calibrating the time axis in degrees of twist. Bone material is visco-elastic, that is, its mechanical properties are time-dependent (McElhaney & Byars 1965, Burstein & Frankel 1968, Sammarco et al. 1971, Burstein et al. 1972b). Previous studies have shown that the maximum torque capacity and stiffness are independent of the angular velocity in the range

3–12 degrees per second (Strömberg & Dalén 1976a). This means that the time-dependence is negligible in the angular velocity range studied. In view of this, the angular velocity was set at 6 degrees per second in the present study. Prior to each test the equipment was calibrated against a known torque, and zero drift of the time base recorder was checked.

The experimental error of the method is less than ~ 3 per cent. This includes the error due to the scatter of the maximum torque capacity of related pairs of diaphyseal bones twisted in the same direction with respect to the bone geometry. Thus the precision of the method is such that any difference larger than ~ 3 per cent between the torsional strength of a test bone and its control is detected inevitably.

RESULTS AND CALCULATIONS

From the torque-twist curve the maximum torque capacity was obtained (Figure 1). The maximum torque capacity is represented by the coordinates of the point on the torque-twist curve corresponding to the onset of ultimate failure of a bone. The first part of the torque-twist curve – from zero up to a critical torque – is linear. The corresponding bone stiffness is expressed as torque per unit twist.

Measurements of twist angle and energy were not studied in this investigation.

The difference in the recorded parameters of related bones was expressed in per cent of the mean value for the pair. The mean value of the difference and the standard deviation for the whole sample of bones were also calculated. The measured values of the inwardly and outwardly twisted samples of long bones were analysed according to the paired *t*-test and the significance determined.

The results are shown in Tables 1 and 2. No significant effect ($P > 0.05$) was found of the direction of twist upon the maximum torque capacity or the stiffness of related bones twisted in opposite directions with respect to the bone geometry. In all bones tested a sudden spiral fracture occurred at the diaphysis.

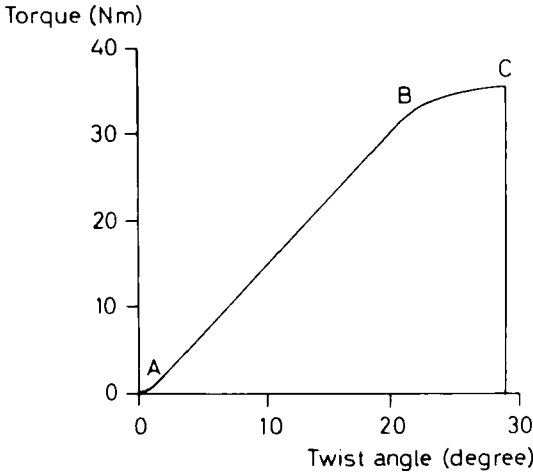


Figure 1. Example of recorded torque–twist curve. Torque is given in newton-meters (Nm) and the twist in degrees. A is the point of onset of torque, A–B is the linear part of the curve and C is the onset of final fracture. The slope of the linear phase A–B of the curve represents the stiffness of the tested long bone.

DISCUSSION

Previous torsional testing of canine long bones has shown that the mechanical properties (e.g., the maximum torque capacity) of previously frozen bones differ from those of fresh bones (Strömberg & Dalén 1976c). As both bones of a pair were treated in exactly the same way prior to testing, it is reasonable to assume that any change in the mechanical properties would be almost identical for both bones. This justifies, according to our opinion, the use of previously frozen bones in the present investigations.

The two bones of a related pair from an animal are reflexion images of each other, and asymmetric as regards their respective longitudinal axes. Thus, in torsion testing, the bones of a related pair can be twisted in different directions; if both bones are twisted either inwardly or outwardly the twist

Table 1. Maximum torque capacity of paired long bones (femora and tibiae) from 20 dogs

| Dog no. | Maximum torque capacity Nm | | Percentage difference | |
|---------|-------------------------------|------------------|-----------------------|--------|
| | Inward rotation | Outward rotation | | |
| femora | 1. | 31.8 | 30.3 | 4.8 |
| | 2. | 24.0 | 25.3 | - 5.3 |
| | 3. | 24.0 | 22.0 | 8.7 |
| | 4. | 28.8 | 29.8 | - 1.7 |
| | 5. | 34.3 | 33.5 | 2.4 |
| | 6. | 24.4 | 24.9 | - 2.0 |
| | 7. | 20.2 | 21.8 | - 7.6 |
| tibiae | 8. | 14.0 | 13.5 | 3.6 |
| | 9. | 23.0 | 24.5 | - 6.3 |
| | 10. | 18.5 | 19.0 | - 2.7 |
| | 11. | 18.5 | 20.0 | - 7.8 |
| | 12. | 22.0 | 20.0 | 9.5 |
| | 13. | 23.0 | 26.0 | - 12.2 |
| | 14. | 19.3 | 21.0 | - 8.4 |
| | 15. | 18.3 | 17.2 | 6.2 |
| | 16. | 26.8 | 26.0 | 3.0 |
| | 17. | 28.7 | 28.3 | 1.4 |
| | 18. | 17.6 | 17.9 | - 1.7 |
| | 19. | 39.6 | 38.9 | 1.8 |
| | 20. | 30.9 | 28.9 | 6.7 |

One of the paired bones was rotated inwardly and the contralateral one was rotated outwardly. The difference between the inwardly rotated bone and the outwardly rotated bone is expressed in per cent of the mean value of the two bones. Angular velocity was 6 degrees/second. The rotational direction had no significant influence on the maximum torque capacity. (Mean = - 0.38 per cent; S.D. = 6.2 per cent. Paired *t*-test: *P* > 0.05).

Table 2. Stiffness of paired long bones (femora and tibiae from 20 dogs)

| Dog no. | Stiffness Nm/degree | | Percentage difference | |
|---------|------------------------|------------------|-----------------------|-------|
| | Inward rotation | Outward rotation | | |
| femora | 1. | 1.42 | 1.54 | -8.1 |
| | 2. | 1.40 | 1.33 | 5.1 |
| | 3. | 1.30 | 1.40 | -7.4 |
| | 4. | 1.33 | 1.38 | -3.7 |
| | 5. | 1.75 | 1.67 | 4.7 |
| | 6. | 1.67 | 1.69 | -1.2 |
| | 7. | 1.53 | 1.53 | 0.0 |
| tibiae | 8. | 0.71 | 0.69 | 2.9 |
| | 9. | 1.00 | 1.08 | -7.7 |
| | 10. | 0.77 | 0.75 | 2.6 |
| | 11. | 0.79 | 0.85 | -7.3 |
| | 12. | 1.00 | 0.96 | 4.1 |
| | 13. | 0.89 | 1.00 | -11.6 |
| | 14. | 0.75 | 0.75 | 0.0 |
| | 15. | 0.58 | 0.56 | 3.5 |
| | 16. | 0.94 | 0.89 | 5.5 |
| | 17. | 1.19 | 1.25 | -4.9 |
| | 18. | 0.69 | 0.70 | -1.4 |
| | 19. | 1.56 | 1.56 | 0.0 |
| | 20. | 1.11 | 1.11 | 0.0 |

One of the paired bones was rotated inwardly and the contralateral one was rotated outwardly. The difference between the inwardly rotated and the outwardly rotated bone is expressed in per cent of the mean value of the two bones. Angular velocity was 6 degrees/second. The rotational direction had no significant influence on the stiffness. (Mean = -1.25 per cent; S.D. = 5.1 per cent. Paired *t*-test: $P > 0.05$.)

direction is the same for both bones with respect to the bone geometry, but if one bone is twisted inwardly and the other outwardly, then the twist direction is different with respect to the bone geometry.

The evident difference in geometry between the two bones of a related pair might be taken to suggest that the torsional strength depends upon the direction of twist. The torsional strength depends, however, not only upon the geometry of the long bone segments, but also upon the internal architecture and distribution of the quantity of bone material of varying quality and the presence and distribution of inhomogeneities in different parts of the diaphyseal bone segments. The

asymmetry of diaphyseal bones is most pronounced in the bone segments where the main muscle attachments are situated and in segments close to the bone ends. The asymmetry, however, decreases steadily as the bone segment where the area of muscle attachment attains a minimum is approached. In this segment the bones are almost cylindrical and the difference in geometry is consequently smallest. As minor variations in geometry of an idealized homogeneous body, according to the theory of strength of materials (Burstein & Frankel 1971), have little effect on the torsional strength, the effect of the remaining difference in geometry is of minor importance.

The cylinder construction is a reasonable compromise to minimize the weight of a body to sustain axial, bend and torque loads acting individually or in combination.

As regards torque, the geometrical asymmetry is obviously compensated for by a corresponding asymmetry of the internal bone architecture so as to render the torsional strength independent of rotation direction. This is evidently a logical consequence of the principle of adaptation to functional demands.

Stiffness is a well defined and easily quantified mechanical property of a body. It defines the twist response of the bone to a given torque. The stiffness of an anatomically asymmetric canine bone is independent of the direction of twist, or, the twist deformation of the bone is of the same magnitude for inward or outward twist with a given torque. This is also an evident consequence of the principle of adaptation to functional demands.

Furthermore, the present results show that the maximum torque capacity and the stiffness of canine long bones are both symmetrical properties, or, independent of the direction of twist. This indicates the ability of a long bone to adapt itself to the load bearing functional demands, in spite of a less favourable outer geometry, caused by the necessary soft tissue attachments. The use of one long bone of a related pair as a torsional test specimen, and the other as a control, with no regard to the direction of twist, is therefore justified.

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