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EXPERIMENTAL MEASUREMENT OF MAXIMUM TORQUE CAPACITY OF LONG BONES

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By means of a new method with high precision (error 3.1 per cent), the maximum torque capacity of an entire long bone from an experimental animal was measured under standardized conditions within 10 minutes after sacrifice of the animal.

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

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Different methods of fracture treatment in diaphyseal bone can be evaluated experimentally by measurement of the maximum torque capacity of treated bones (cf. Sammarco et al. 1971, Uhtoff & Dubuc 1971). Such studies may also be of interest with respect to different pathological conditions, such as endocrine disturbances, malnutrition and various forms of neural or muscular dysfunction.

We have developed a method by which the maximum torque capacity can be measured with high precision, and so quickly after sacrifice of the test animal that post-mortem changes cannot reasonably be held to affect the physical properties of the bone (cf. Sedlin & Hirsch 1966, Smith & Walmsley 1959).

METHODS

Measuring equipment

By means of a specially constructed apparatus, the torque is determined as a function of the angle of torsion of a test body. The apparatus consists of three units:

1. Torsion machine.
2. Signal generator.
3. Time base recorder.

The torsion machine (Figure 1) is driven by a synchronous motor with 1500 synchronous revolutions per min at 50 Hz.

The action of the synchronous motor is seen in Figure 2. The angular velocity is independent of the torque for all loads smaller than the maximum torque. The load in our experiments never exceeded the maximum torque and thus the test body was always torqued at a constant angular velocity. The moment, as a function of time, was recorded during each experiment. As the angular velocity is constant during each experiment, the moment as a function of angle is easily calculated.

The synchronous motor is fed by a signal generator by means of which angular velocity can be regulated in a stepless manner. The output shaft drives a gear box with a transmission ratio of 300:1. The pinion is fixed on the output shaft, and the gearwheel, supported by the machine stand, is connected to one end of the test body. The apparatus is so constructed that the gear engagement force does not load the test body, which is thus loaded only by the torsional moment. The other end of the test body is firmly attached to the stand by means of a fixation device and transparent acrylic tube. The angular velocity of the torsion machine can be varied

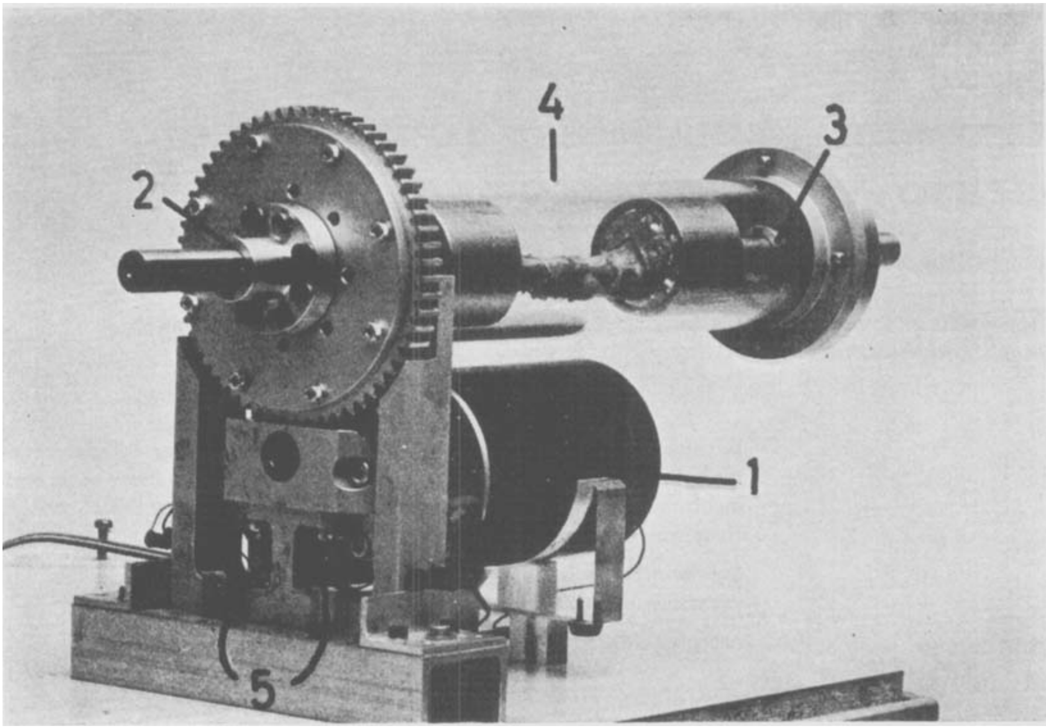

Figure 1. The torsion machine. 1) Synchronous motor. 2) Fixation device (rotating). 3) Fixation device (stationary). 4) Acrylic tubing. 5) Strain gauges.

from 2.4° to 15° per second. At an angular velocity of 6° per second the maximum torque is 50 Nm. The acrylic tube together with the fixation devices form a closed chamber, the environment of which can be regulated.

The motor is attached to the stand by a beam. During an experiment the torque of the motor causes a torque in the test body and a bending moment in the beam. The strain on the beam

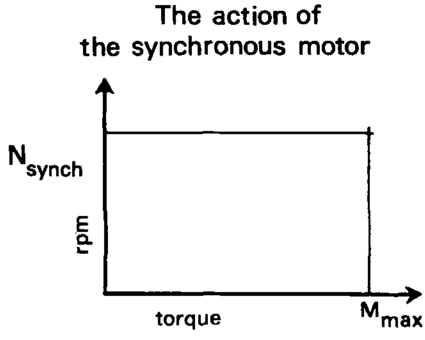

Figure 2. The action of the synchronous motor.

surface to the bending moment is recorded by means of strain gauges, arranged in a Wheatstone bridge (Figure 3).

As the torque in the test body is directly proportional to the bending moment in the beam, the output from the bridge gives directly the torque in the test body. The total deformation of the stand, beam and acrylic tube is negligible in comparison with that of the test body.

The torque, as a function of time (Figure 4), is registered by means of a time base recorder, fed by the signal from the strain gauge bridge.

Calibration

Before each experiment the apparatus was calibrated against a given torque of 10 Nm.

For this purpose a shaft was inserted into the holes of the end plates of the acrylic tube. One end of the shaft was locked to the cog-wheel by a wedge. In the other end there is a slit, in which the mid-point of an approximately 1 m long rod was fixed, so that the rod axis was perpendicular to that of the shaft. At one end of the rod a weight of 2 kg was suspended (Figure 5).

The apparatus was started. When the rod was

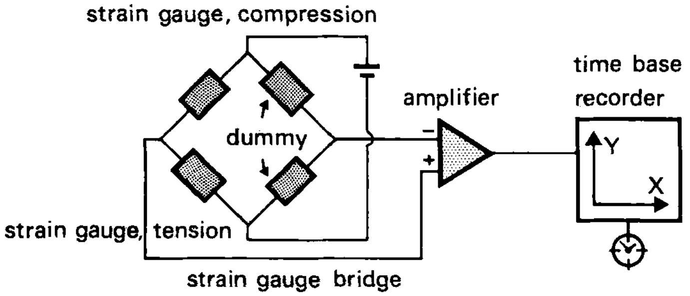

Figure 3. Wiring diagram for measuring equipment.

horizontal, the torsional load was 10 Nm and a reading was taken on the time base recorder. An amplification was chosen to give full deflection of the recorder at about 40 Nm, which corresponds to the maximum torque capacity of femora from dogs similar to those treated. The deflection written on the recording paper had full linearity. The paper speed chosen was 50 mm per second, and each second was marked on the paper. An experiment was completed within 5 minutes after calibration.

Fixation of the test bone in the torsion machine

The test bone was fixed in the torsion machine by means of two cylinders provided with concentric shafts with splines.

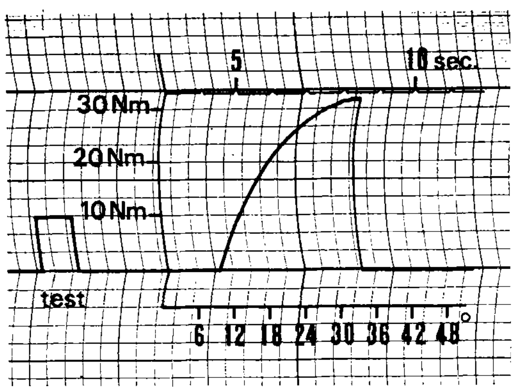

Figure 4. Example of moment-time curve.

The cylinders were placed in a U-shaped gutter, so that the surface of their casings was in line contact with the edges of the gutter. The epiphyses of the test bone were each placed in the cavity of a cylinder, after which the cylinders were fastened in the U-shaped gutter by means of clamps. The journals of the cylinders were thus aligned concentrically. The test bone, with a cylinder at each end, was placed in the vertical position. The space between the end of the bone and the inner surface of the cylinder was successively filled with a liquid metal alloy of low viscosity, Cerro Low 117 (Mining & Chemical Products Ltd., Great Britain) (Figure 6).

This alloy is eutectic and soidifies at 47.5° C. The volume remains practically constant during solidification, and in the solid state the alloy has an elastic modulus which is greater than that of cortical bone. The cylinders and the liquid alloy in them were cooled to 37° C in a bath of physiological saline, upon which each end of the test bone became fixed in its own metal cylinder, without any residual stress or heat affecting the test bone.

To prevent the metal cast from rotating with respect to the cylinders, two screws were applied axially in the bottom of each cylinder and fixed into the cast metal. The resulting assembly, the test bone with the two cylinders, was mounted in the torsion machine. The two protruding concentric journals of the cylinders passed through holes in the sides of the acrylic tube, and were locked to these. The length of the cylinders and their journals is greater than the distance be-

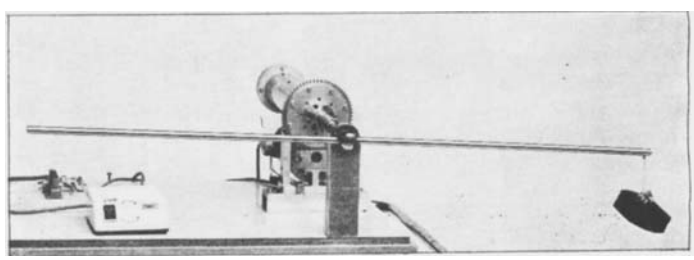

Figure 5. Calibration of the torsion machine.

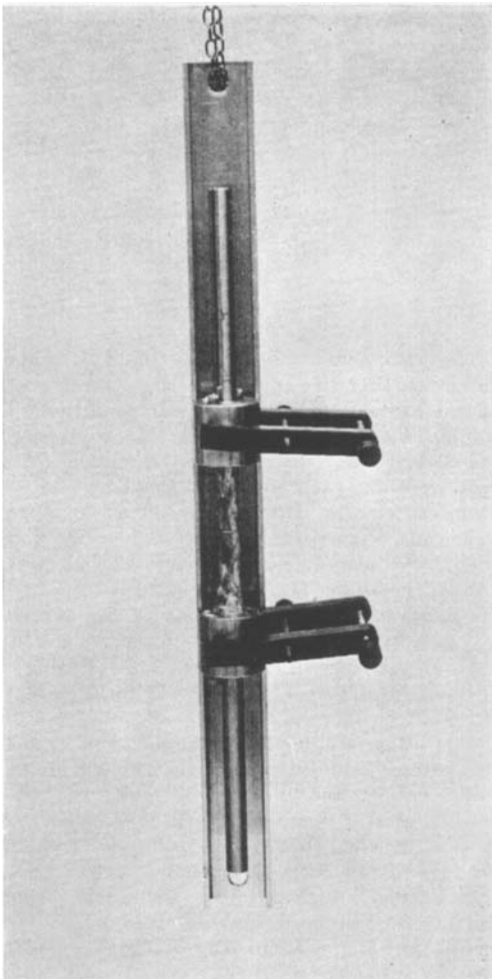

Figure 6. Holding devices in the U-shaped gutter.

tween the end plates of the acrylic tube. This permits investigation of bones of varying length (Figure 1).

As no relative torsional motion can occur in the joints between the test bone and apparatus, the torque and angular velocity are transmitted to the test bone unaffected.

Calculation

For each experiment, torque versus angular velocity was recorded. The maximum amplitude of the curve (Figure 4) (giving the maximum torque capacity) was determined to the nearest 0.1 mm. This figure was transformed to Nm by means of calibration data. The onset of torsion was noted on the recording paper as an incipient curve deviation. The distance between the starting point for incipient torsion, and the projection on the zero line of the point on the curve where the resistance to torsion ends is a measure of the maximal angle of torsion, which can easily be transformed to degrees. The difference in maximum torque capacity, and in maximum angle of torsion, between the test bone and the control bone from the same individual has been expressed as a percentage of the value for the control bone.

Precision

The precision of the method in measuring the torsional strength of long bones was tested. Tibiae with closed epiphyseal lines from long-legged, healthy dogs of varying breeds and ages and of both sexes were tested as described above, after the animals had been killed with an intravenous injection of thiomebumalnatrium (Pentothalsodium ®, Abbott Laboratories, USA). All bones were subjected to medial rotation at a constant angular velocity of 6° per second until they fractured. Spiral fractures approximately in the middle of the shaft occurred in all bones. In no case were intermediate fragments obtained. After the fracture, the bones were examined macroscopically and by plain radiography. No fracture fissures extending into the metal cylinders were observed .

Table 1. Maximum torque capacity of right and left tibiae of 18 dogs. The difference between right and left tibiae from the same animal is expressed as the percentage deviation from the mean of the two bones. Angular velocity 6°/s.

Dog no.	Right tibia Nm	Left tibia Nm	Percentage deviation from the mean of the two bones
1	13.5	13.2	1.1
2	10.0	10.1	–0.5
3	16.2	15.6	1.9
4	18.6	18.3	0.8
5	21.3	22.5	–2.7
6	18.4	20.9	–6.4
7	15.8	15.8	0.0
8	15.3	14.6	2.3
9	11.7	11.5	0.9
10	24.9	25.4	–1.0
11	19.1	19.1	0.0
12	18.2	19.8	–4.2
13	17.3	17.3	0.0
14	34.4	33.5	1.2
15	31.0	31.5	–0.8
16	13.7	13.6	0.4
17	28.2	27.5	1.2
18	12.1	12.5	–1.6

The maximum torque capacity was determined in 36 tibiae from 18 dogs, and the differences in this respect between bones from the same dog were observed (Table 1). The highest and lowest torques measured at the time of fracture in this series were 34.4 and 10.0, respectively. The difference in torsional strength between the right (X_1) and left (X_2) tibiae in per cent of the mean value for one animal was calculated by the formula $d = \frac{X_1 - X_2}{(X_1 + X_2)\ 0.5} \cdot 100$. The mean value for the right tibia was 0.8 per cent lower than that for the left, but this difference is not significant ($P > 0.05$). By means of the formula $\sqrt{\frac{\Sigma d^2}{2n}}$, where n is the number of measured pairs of bones, the error of the method was found to be 3.1 per cent. Measurements of angles of torsion and of energy were not studied in this investigation.

To determine the possible effect of different angular velocities, the difference in torsional strength between tibiae from the same dog was calculated as above, but with one angular velocity for one tibia and another velocity for the other. Eighteen tibiae from nine dogs were studied. The material was thus divided into two groups, so that the right and left tibiae of the same dog were never in the same group. In one group the torsional strength was measured at an angular velocity of 6°/s, and in the other at velocities of 3, 6 and 12°/s (Table 2). The difference between the right and left tibia from the same animal is expressed as the percentage deviation from the mean of the two bones (Table 2).

Table 2. Maximum torque capacity for right and left tibiae at various angular velocities. The difference between right and left tibiae from the same animal is expressed as the percentage deviation from the mean of the two bones.

Dog no.	Group I		Group II		Percentage deviation from the mean of the two bones
	degr./s	Nm	degr./s	Nm	
101	6	13.2	3	13.7	−1.8
102	6	28.8	3	28.0	1.4
103	6	17.6	3	17.5	0.3
104	6	15.5	6	16.1	−1.9
105	6	11.3	6	11.7	−1.7
106	6	17.3	6	17.0	0.9
107	6	22.7	12	22.7	0.0
108	6	21.2	12	21.2	0.0
109	6	21.8	12	21.4	0.9

Table 3. Applied and recorded torque showing the good linearity of the measuring equipment.

Observation no.	Applied torque Nm	Recorded torque Nm
1	40.0	40.0
2	38.4	38.2
3	37.6	37.4
4	36.8	36.4
5	34.4	34.1
6	32.0	31.7
7	29.6	29.1
8	26.4	26.2
9	23.2	23.1
10	20.0	19.9
11	16.0	16.1
12	12.0	12.3
13	8.0	8.2
14	4.0	4.1
15	0.0	0.0

Halving or doubling of the angular velocity of 6°/s had no appreciable effect on the torque required for fracture; all deviations from the mean value for the two bones of the same animal were smaller than 1.9 per cent (Table 2) (cf. Burstein & Frankel 1968).

Linearity

The linearity of the equipment for measurement of maximum torque capacity was determined in the range from 0 Nm to 40 Nm at random intervals. For this, a 1 metre long steel rod was inserted into the torsion machine perpendicularly to the rotation shaft with its midpoint fixed in the mobile fixation device. The rod was then loaded with different loads of known magnitude, placed at one end of the rod, and the recordings were read off.

The results, showing the good linearity of the measurement equipment, are given in Table 3 and Figure 7.

DISCUSSION

The strength is one parameter for the experimental assessment of the results of different methods of fracture treatment in long bones. In this case the torsional strength is most suitable for the follow-

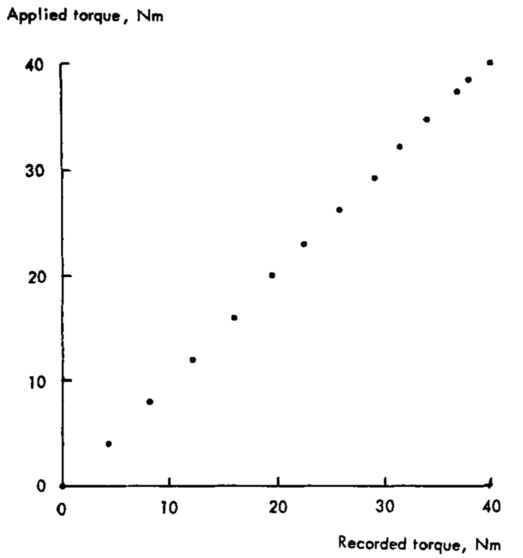

Figure 7. Linearity of the torsional measurement equipment. The applied known torques are given on the ordinate and the recorded torques on the abscissa.

ing reasons (cf. Burstein & Frankel 1971):

1. The torque is constant in every section of the test body;
2. Minor variations in the geometry of the bone have little effect on the torsional strength;
3. The torque and angular velocity are easily measured;
4. Torsional moments occur in the majority of the types of force that cause fractures clinically (cf. Asang 1974, Braden et al. 1973, Frankel & Burstein 1965, McElhaney & Byars 1966, Mather 1967, Mather 1967).

We have performed pilot studies in which different fixation devices have been tested. In these experiments, residual stresses in bone and fixation devices have affected the results in an unacceptable way. Fixation with pins passing through the bone, or with attached joints, affects the stress distribution and thus the measured torsional strength of the test bone. The resulting residual stresses are of sufficient magnitude to affect the fracture course even before the test. We have not succeeded in standardizing these fixation methods. In order to eliminate these sources of error, we cast the ends of the bone in a mould of epoxy resin. In this way we achieved a joint consisting of a mechan-

Table 4. Component data.

Torsion machine:
Max. torque: 50 Nm.
Revolutions: 1 rpm.
Stiffness of acrylic plastic tube: 0.004°/Nm.
Power source:
Synchronous motor type R 864, Neckar-Motoren, Karl Jauch & Co., Postfack 21, 7212 Deisslingen, W. Germany.
Revolutions 1500 rpm.
Torque 700 cmp.
Power 12 Watt.
Voltage 220 Volt 50 Hz.
Gear:
Type Z8, Neckar-Motoren, Karl Jauch & Co.
Gear ratio 300:1.
Efficiency 90 per cent.
Strain gauge:
Type F–10, Showa–Sokki, Toyota Central Research and Development Inc., 12 Hisakata 2 – Chome, Showa – Q Nagoya, Japan.
Length 10 mm.
Resistance 119.8 ohm.
Gauge factor 2.11.

Signal generator:
Type 1308–A, Audio Oscillator and Power Amplifier, General Radio Company, West Concord, Massachusetts, USA.

Time base recorder:
Model 7–B Polygraph with model 7 PIC preamplifier, Grass Instruments, Quincy, Massachusetts, USA.

Metal alloy:
Cerro Low 117, Mining & Chemical Products Ltd., Alperton, Wembley, Middlesex, Great Britain.
Components: Bi, Pb, Sn, Cd, In.
Melting point: 47.5° C (eutectic).
Modulus of elasticity: 29500 Nm/mm^2.
Expansion: expands somewhat during solidification to 0.02 per cent after 6 minutes, then shrinks; after 30 minutes the volume change is ± 0.0 per cent and after 2 hours it is stabilized at — 0.02 per cent.

ical fixation device acting upon the epoxy resin sleeve. This method had its drawbacks, however. The rapidly solidifying epoxy resin did not acquire a satisfactory modulus of elasticity within the desired time under physiological temperature conditions. Changes in the environment of the bone influenced its strength (Sedlin & Hirsch 1966). Heat, drying and mechanical stress each had their own significant effect. These sources of error were minimized by the use of Cerro Low 117, as described above, and by performing the experiments in a temperature-controlled, humid chamber.

Our tests demonstrate the good linearity of the torsional measurement equipment and the good reproducibility of the method. The agreement between the right and left tibiae with respect to maximum torque capacity justifies the use of the method in experimental studies of changes in maximum torque capacity in one bone, with the other, contralateral bone from the same dog serving as a control. With this method it is possible, with high precision and under standardized conditions, quickly to carry out studies of bone strength *in vitro* before post-mortem changes of any importance occur and without subjecting the bone to any damage that may alter its physical properties.

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