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Mechanical properties and bone densities of canine trabecular bone

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The purposes of this study were (1) to evaluate the mechanical properties of canine epiphyseal cancellous bones from adult canine femoral heads, femoral condyles, tibial plateau, and humeral heads, using indentation and compression tests, and (2) to measure bone densities (apparent density and ash density) of these cancellous bones so as to develop a normal data base of mechanical strength and bone density. The correlations between the two mechanical tests and between these tests and bone densities were also considered. The results showed all of the three mechanical parameters, ultimate load, stiffness, and ultimate strength, measured by the indentation test were higher than those measured by the compression test. Correlation analysis showed that the two sets of mechanical values correlated well ($r = 0.823$–0.952, $p < 0.01$). The apparent density and ash density correlated well with the mechanical parameters determined by the two types of mechanical tests ($r = 0.737$–0.966, $p < 0.05$).

1. Introduction

Many bone-related conditions both in dogs and humans, such as fractures and osteoporosis, could be explained biomechanically or could be managed more successfully using biomechanical principles, such as the biomechanical knowledge used in fracture fixation or prosthesis design. Also, bone densities are important indicators for many pathological bone conditions, such as osteoporosis. Unfortunately, the mechanical properties and densities of cancellous bone in the dog have not been well characterized [1–3]. Basic research on the mechanical properties and bone densities of canine cancellous bones must be performed (1) to understand better the cause and healing of fractures, (2) to develop techniques for internal fixation of fractures or osteotomies, (3) to develop better designs of prosthesis of total joint replacement [4], or (4) to help research on some pathological conditions such as osteopenia or osteoporosis [4, 5]. All of these aspects have great potential to enhance the well-being of both the animal itself and humans. Before substantial advances in internal fixation, external fixation, or joint replacement can be made, or the aforementioned orthopaedic research can be done using a canine model, better understanding of the mechanical properties and densities of canine cancellous bone is needed.

The purposes of this study were (1) to evaluate the mechanical properties (using indentation and compression tests) of canine epiphyseal cancellous bones, and (2) to measure densities (apparent density and ash density) of these cancellous bones so as to develop a normal data base of mechanical strength and bone density.

2. Materials and methods

2.1. Sample preparation

Eight pairs each of femoral, tibial and humeral bones (fresh frozen in saline at $-20\,^{\circ}$C for 12 ± 4 wk) of adult dogs (mixed breed, 18–23 kg), used as healthy controls for other studies, were used. The bones were thawed in normal saline and kept moist during sample preparation and testing. The bones were ground and cut to obtain slices from the epiphyseal area (Fig. 1). A total of eight slices (5 mm thick) were harvested from the limbs on one side of each animal, containing a total of ten points for indentation test (the tibial plateau contained three points). From the contralateral side, at the equivalent sites, ten bone cylinders (4 mm diameter, 5 mm length) were trephined from the eight slices, for compression testing (Fig. 2). The slices from left or right limbs were randomly chosen for indentation or compression tests.

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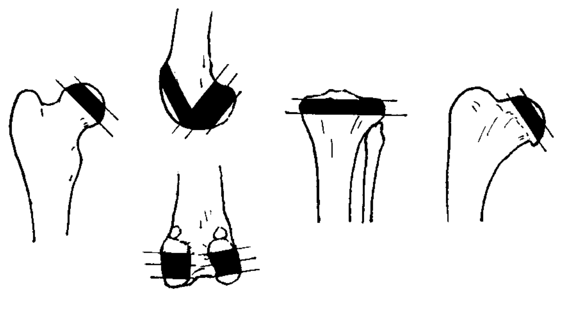

Figure 1 Schematic illustration of slices created for indentation and compression tests at different locations. The surfaces of the slices to be tested were on the plane perpendicular to the line of weight-bearing.

2.2. Mechanical testing

A mechanical test machine (MTS System 810, Minneapolis, MN) was operated under displacement control. After the specimen was placed on the lower platen (polished steel) and the surface of the indentor (4.24 mm diameter), or the upper platen (polished steel) was positioned to the specimen surface and loading was started at a constant rate of 1 mm min $^{-1}$ (monitored by a built-in LVDT) (Fig. 3) [6, 7]. The loading was stopped when the curve dropped from the maximum load (the highest point of the curve). A stiffness measure was obtained from the linear portion of the curve. Ultimate indentation strength, σ_i, or ultimate compression strength, σ_c, were calculated by

$$\sigma = 4P/\pi d^2 \quad (1)$$

where P is the maximum load and d is the diameter of the indentor or the bone cylinder.

The elastic modulus from the compression test, E_c, was calculated using

$$E_c = S_c L/A \quad (2)$$

where S_c is the compression stiffness, L is the length of the bone cylinder and A is the end-face area of the bone cylinder.

2.3. Evaluation of bone densities

After the compression test, bone cylinders were put into 1.0% sodium hypochlorite for 18 h to remove the marrow, followed by defatting for 4 h in a 50/50 ethanol/acetone solution. The cylinders were rehydrated in water under vacuum for 10 min, followed by centrifugation at 3700 r.p.m. for 30 min to remove excess water. The samples were then weighed to obtain the wet weight. Apparent density was calculated by dividing the wet weight by the sample volume ($V = LA = L\pi d^2/4$, where L is the length of the bone cylinder, A is the end-face area of the bone cylinder and d is the diameter of the bone cylinder). The samples were ashed in a furnace at 500 °C for 48 h. The ash was weighed and ash density was calculated by dividing the ash weight by the sample volume.

2.4. Data analysis

Pearson correlation coefficients were calculated between the two mechanical tests and between the two tests and the bone densities.

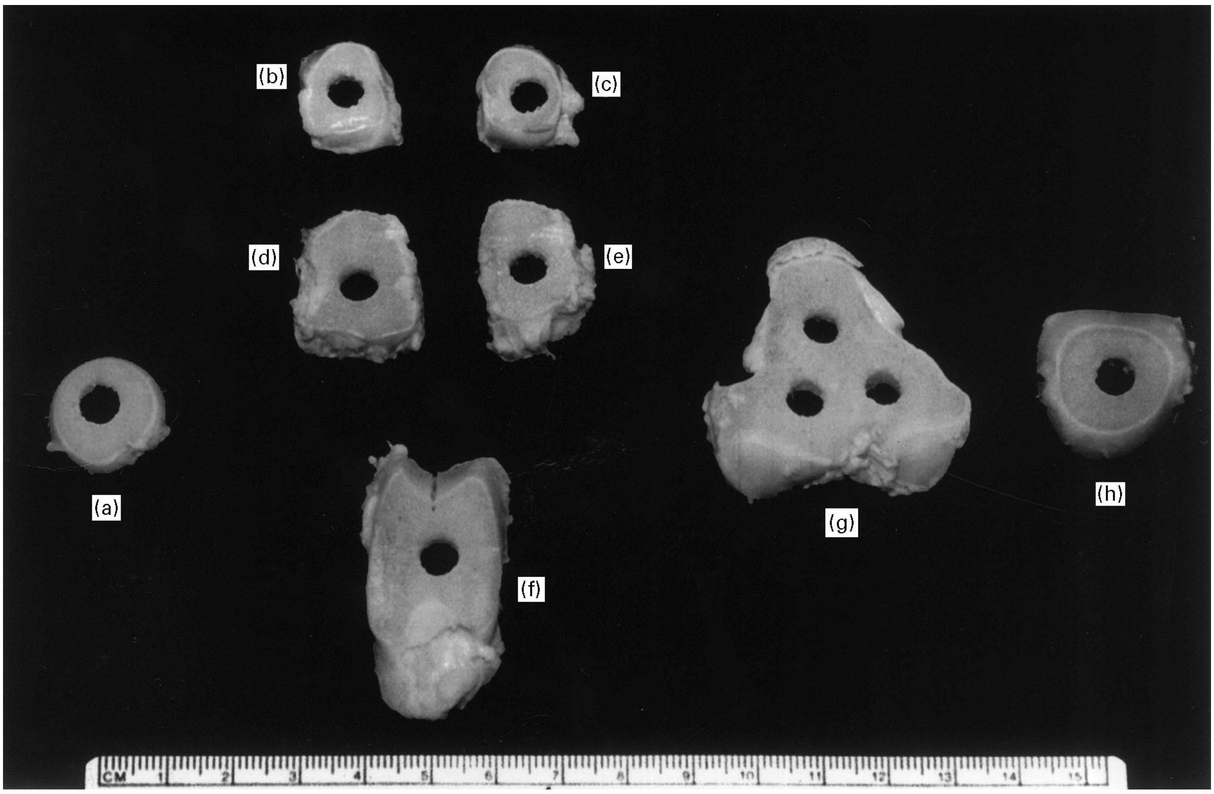

Figure 2 The photograph shows where the cylindrical samples were taken. (a) femoral head. (b) medial femoral condyle level 1, (c) lateral femoral condyle 1, (d) medial femoral condyle level 2, (e) lateral femoral condyle level 2, (f) intercondylar groove, (g) tibial plateau, (h) humeral head.

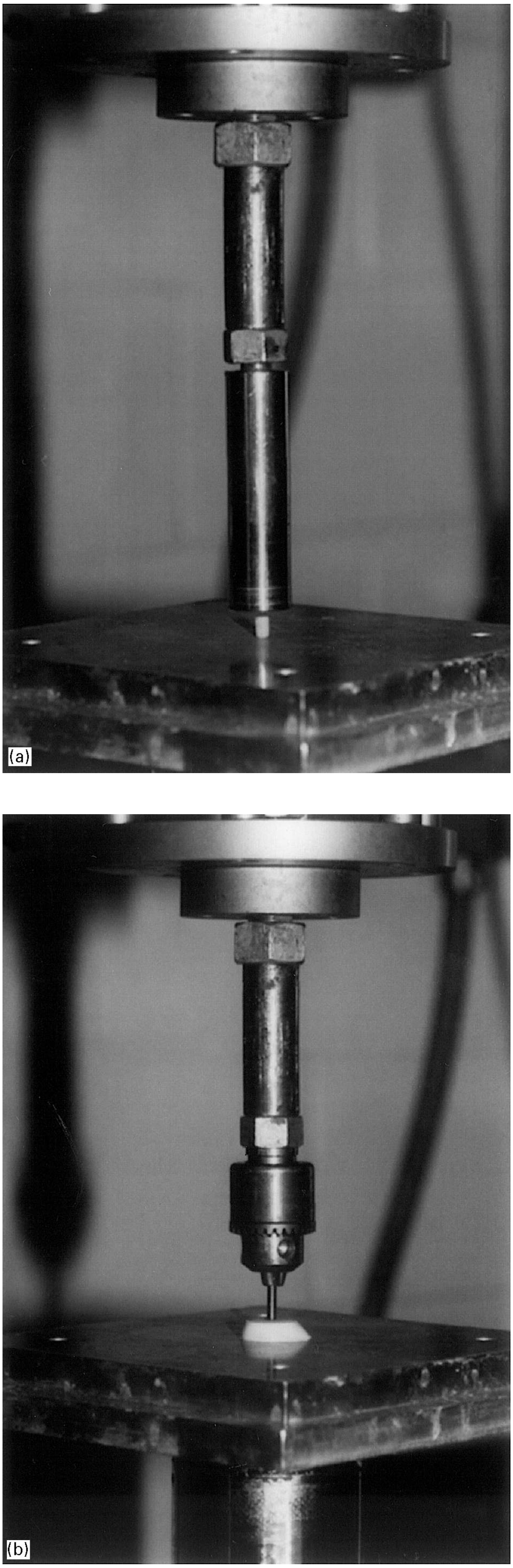

Figure 3 Mechanical testing setup equipment. (a) Compression test, (b) indentations test.

3. Results

For different epiphyseal locations, the elastic moduli from the compression test were different, with the highest values for the femoral head and the lowest for the anterior tibial plateau (Table I). The ultimate strengths from the indentation test were higher than those obtained by conventional compression testing (Table I). Correlation analysis showed that the two sets of mechanical data from the indentation and compression tests correlated well (Table II). The data of apparent density ($0.78 \pm 0.22\ g\,cm^{-3}$) and ash density ($0.44 \pm 0.12\ g\,cm^{-3}$) (Table III) both correlated well with all three mechanical parameters from both mechanical tests (Table IV).

4. Discussion

There are very few reports on the mechanical properties of canine epiphyseal trabecular bones. In this study, a data set was generated using conventional compression testing. For the same locations (distal femur and proximal tibia), the values of ultimate strength and elastic modulus are basically in accord with those reported by Vahey *et al.* [1] and Kuhn *et al.* [2]. Comparing the values of the distal femur and tibial plateau, the ultimate strength of human bones (4 MPa) [8] is lower than that of canine bones (17 MPa). Sumner *et al.* [3], Aitken *et al.* [9], Nakayabashi *et al.* [10], and Finalay *et al.* [11], have reported comparable data of trabecular bones using the indentation test. From the present study, a comparable data set was generated by using indentation tests. Compared to human bones, canine bones are stronger (ultimate strength 37–67 MPa versus 5–40 MPa for distal femur) [10].

The values obtained by indentation test are higher than that from the compression test. One possible reason is that the column of bone tissue under the end surface of the indentor is constrained by the surrounding bone (a kind of constrained compression test). Also, a shear force develops around the edge of the indentor while the indentor is being pressed into the bone surfaces. The correlation analysis is in accordance with that of Sumner *et al.* [3], in which the mechanical values obtained by the indentation test correlated very well with those by compression testing. A similar testing procedure, a penetration test described by Hvid *et al.* [12], was used to detect cancellous bone strength during knee arthroplasty. They also found a good correlation between the data of the penetration test and the conventional compression test.

The apparent density and ash density of the bone correlate well with the mechanical parameters both by indentation and compression testing (Table III). The correlation between parameters obtained by compression testing and bone densities have been established in the literature [13–16]. By a statistical analysis of the pooled data from several studies, Rice *et al.* [14] found that both the elastic modulus and strength are proportional to the square of apparent density, and therefore proportional to one another.

TABLE I Mechanical parameters of the indentation test of canine cancellous bones (mean ± S.D., $n = 8$ pairs of each part of the bone)

Bones	Test	Ultimate load (N)	Stiffness ($N\,mm^{-1}$)	Ultimate strength (MPa)	Elastic modulus (MPa)
Femoral head	Compression	360 ± 43	1139 ± 678	29 ± 4	428 ± 237
	Indentation	1205 ± 205	4910 ± 1257	85 ± 15	
Med. femoral condyle level 1	Compression	357 ± 89	919 ± 266	28 ± 7	354 ± 132
	Indentation	953 ± 167	3550 ± 1342	67 ± 11	
Lat. femoral condyle level 1	Compression	303 ± 50	984 ± 196	24 ± 4	394 ± 105
	Indentation	788 ± 128	3964 ± 495	56 ± 9	
Med. femoral condyle level 2	Compression	237 ± 70	808 ± 286	19 ± 5	317 ± 98
	Indentation	565 ± 102	2997 ± 837	40 ± 7	
Lat. femoral condyle level 2	Compression	185 ± 57	696 ± 414	14 ± 4	279 ± 185
	Indentation	522 ± 51	2285 ± 689	37 ± 4	
Femoral intercondylar groove	Compression	168 ± 34	561 ± 121	13 ± 3	210 ± 47
	Indentation	581 ± 125	2586 ± 825	41 ± 9	
Medial tibial plateau	Compression	132 ± 47	603 ± 396	10 ± 3	215 ± 153
	Indentation	369 ± 131	1530 ± 279	26 ± 9	
Lateral tibial plateau	Compression	281 ± 156	1394 ± 649	24 ± 6	426 ± 208
	Indentation	619 ± 166	2790 ± 999	44 ± 11	
Anterior tibial plateau	Compression	59 ± 21	233 ± 94	5 ± 2	106 ± 51
	Indentation	247 ± 98	1024 ± 447	17 ± 7	
Humeral head	Compression	225 ± 74	838 ± 399	18 ± 6	350 ± 171
	Indentation	612 ± 110	2947 ± 309	43 ± 8	

TABLE II Correlation analysis between the mechanical parameters of the two tests ($n = 10$, $n' = n - 2$, one-way analysis). The p values are at least < 0.01.

Mechanical parameter	Ultimate load	Stiffness	Ultimate strength
Correlation coefficient (r)	0.952	0.823	0.871

TABLE III Correlation analysis between the mechanical parameters and bone densities ($n = 10$, $n' = n - 2$, one-way analysis). p values are at least < 0.05.

Parameter	Test	Apparent density	Ash density
Ultimate load	Compression	0.966	0.966
	Indentation	0.940	0.954
Stiffness	Compression	0.868	0.853
	Indentation	0.944	0.923
Ultimate strength	Compression	0.934	0.912
	Indentation	0.939	0.954
Elastic modulus	Compression	0.778	0.737

There were very few reports on the correlation between indentation test values and bone densities [16]. Behrens *et al.* found a fair correlation between indentation strength and bulk specimen density (fat-free dry bone weight/unit volume) of human knee trabecular bones. But the bulk specimen density is not exactly the apparent density of the bone which is fat-free wet bone weight/unit volume. The present study verified that the correlation between the mechanical values obtained by indentation test and the bone densities are significant (Table III). One explanation for the stronger and stiffer nature of canine trabecular bones may be that the values of apparent density are much higher in dog bones ($0.78\ g\,cm^{-3}$) (Table IV) than human bones (0.05–$0.60\ g\,cm^{-3}$) [17].

TABLE IV Apparent density and ash density of canine epiphyseal trabecular bones (mean ± S.D., $n = 8$).

Bones	Apparent density ($mg\,mm^{-3}$)	Ash density ($mg\,mm^{-3}$)
Femoral head	1.17 ± 0.17	0.65 ± 0.09
Med. femoral condyle level 1	0.98 ± 0.07	0.56 ± 0.07
Lat. femoral condyle level 1	0.89 ± 0.12	0.50 ± 0.08
Med. femoral condyle level 2	0.77 ± 0.17	0.44 ± 0.10
Lat. femoral condyle level 2	0.69 ± 0.13	0.41 ± 0.10
Intercondylar groove	0.69 ± 0.12	0.40 ± 0.05
Medial tibial plateau	0.52 ± 0.11	0.31 ± 0.09
Lateral tibial plateau	0.83 ± 0.20	0.44 ± 0.13
Anterior tibial plateau	0.41 ± 0.11	0.22 ± 0.04
Humeral head	0.84 ± 0.17	0.43 ± 0.06
Mean ± S.D.	0.78 ± 0.22	0.44 ± 0.12

In conclusion, a normal data base for mechanical properties using indentation and compression tests and bone densities of selected canine epiphyseal trabecular bones was generated from this study. The two sets of mechanical values from the two tests correlated very well. The data of apparent density and ash density also correlated well with the parameters obtained by both mechanical tests.

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