Journal of Biomechanics 34 (2001) 799–803

JOURNAL OF BIOMECHANICS

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Technical note

Mechanical properties of cancellous bone in the human mandibular condyle are anisotropic

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Accepted 14 February 2001

Abstract

The objective of the present study was (1) to test the hypothesis that the elastic and failure properties of the cancellous bone of the mandibular condyle depend on the loading direction, and (2) to relate these properties to bone density parameters. Uniaxial compression tests were performed on cylindrical specimens ($n = 47$) obtained from the condyles of 24 embalmed cadavers. Two loading directions were examined, i.e., a direction coinciding with the predominant orientation of the plate-like trabeculae (axial loading) and a direction perpendicular to the plate-like trabeculae (transverse loading). Archimedes' principle was applied to determine bone density parameters. The cancellous bone was in axial loading 3.4 times stiffer and 2.8 times stronger upon failure than in transverse loading. High coefficients of correlation were found among the various mechanical properties and between them and the apparent density and volume fraction. The anisotropic mechanical properties can possibly be considered as a mechanical adaptation to the loading of the condyle in vivo.

Keywords: Mandibular condyle; Cancellous bone; Mechanical properties; Density

1. Introduction

Previous studies revealed that in the mandibular condyle the cancellous bone is anisotropic (Hongo et al., 1989b; Giesen and van Eijden, 2000). It consists of parallel plate-like trabeculae primarily oriented in the vertical direction, perpendicular to the mediolateral condylar axis. In the horizontal direction the plate-like trabeculae are interconnected with rods. In addition, a wide range in bone volume fraction was found between condyles of different individuals (Giesen and Van Eijden, 2000). Hence, a wide range in apparent density, and as a consequence, in mechanical properties can be expected.

Thus far, to our knowledge no studies are available on mechanical properties of the cancellous bone of the human mandibular condyle. Adequate estimates of these are, for example, required in finite element modeling of the condyle and in tissue engineering of mandibular implants. The purpose of this study was to determine the mechanical properties of the cancellous bone of the mandibular condyle in different directions and to relate these to the density of the bone. The hypotheses were that the stiffness and strength would be higher for loading in the vertical direction (axial loading) than for loading in the mediolateral direction (transverse loading).

2. Methods

2.1. Specimen preparation

Cylindrical cancellous bone specimens were obtained from the mandibular condyles of 24 embalmed human cadavers (19 female, 5 male, mean age $\pm$ S.D.: 74.8 ± 11.7 yr). The embalming fluid was a mixture of water, alcohol, glycerin, and formol. The cadavers were selected according to the state of dentition; the mean number of teeth in the upper jaw was 8.5 and in lower jaw 10.7.

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0021-9290/01/$ - see front matter
PII: S0021-9290(01)00030-6

To produce cylindrical bone specimens a custom-made hollow drill was used. Two different groups of specimens were fabricated, drilled in two directions, i.e., supero-inferiorly (axial group, $n = 24$) and mediolaterally (transverse group, $n = 23$) (Fig. 1). The resulting specimens had a diameter of 3.57 ± 0.08 (mean $\pm$ S.D.) mm. The position within the condyle for the axial specimen, medial or lateral, was chosen by randomization. Mostly, both specimens originated from the same condyle. In a few cases ($n = 3$) the specimens came from both condyles of the same individual. The specimens were cut perpendicular to their long axes with a Leitz Saw Microtome 1600 (Ernst Leitz Wetzlar Gmbh, Wetzlar, Germany). The specimen lengths were measured using a caliper (mean $\pm$ S.D.: 4.88 ± 0.04 mm). The specimens were stored in the embalming fluid prior to testing.

2.2. Mechanical testing

The specimens were subjected to uniaxial destructive compressive mechanical tests in a material testing machine (858 Mini Bionix, MTS Systems Corporation, Minneapolis, MN, USA) using a 1 kN load cell. They were placed between two steel loading rods with low friction using low-viscosity mineral oil as a lubricant. A strain gage extensometer (model 632.11F-20, MTS) was attached to the loading rods close to the specimen to monitor its deformation and to calculate the strain. The specimens were preconditioned with 5 cycles between a pre-load of 3 N (zero strain) and 0.6% bone strain to reach a viscoelastic steady state (Linde et al., 1988). Then a load was applied with a constant strain rate of 0.2% s^{-1} until a strain of 3% was reached. From the stress-strain curve four mechanical parameters were calculated, i.e., elastic-(E-)modulus, ultimate stress, ultimate strain, and failure energy. The E-modulus was defined as the tangent of the stress–strain curve at a strain of 0.6% (Linde et al., 1988; Ding et al., 1997).

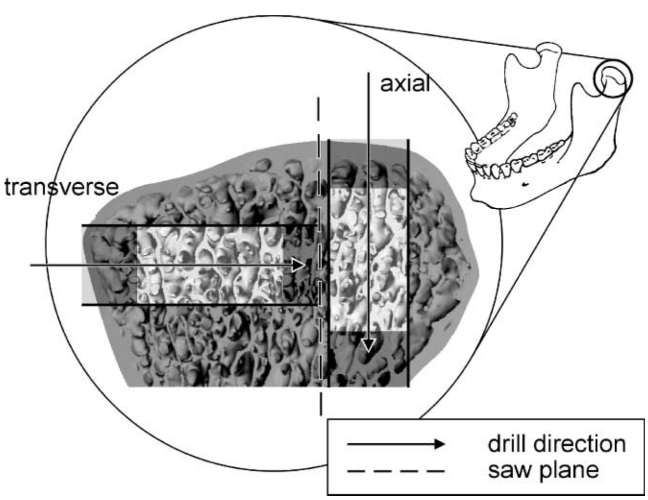

Fig. 1. The specimens were drilled from the condyle (anterior view) in two directions 1) superio–inferior (axial) and 2) mediolateral (transverse). After the axial specimen was drilled out, the condyle was sawed off perpendicular to the direction of the second specimen. Finally, the ends of the core were cut-off perpendicular to the cylindrical axis leaving the actual specimen (enlightened).

After the mechanical testing Archimedes' principle was applied to determine cancellous bone density parameters: apparent density, tissue density, and volume fraction (Ding et al., 1997).

2.3. Statistical analysis

Paired *t*-tests were used to test for differences between loading direction (axial vs. transverse), mandibular side (left vs. right), and condylar site (lateral vs. medial). Due to non-equal variance the mechanical parameters and the density parameters were logarithmically transformed and Pearson's coefficients of correlation were calculated (Hodgskinson and Currey, 1990; Kabel et al., 1999). SPSS 10.0 software (SPSS Inc.) was used to perform all statistical analyses.

3. Results

In Table 1 the descriptive statistics of the mechanical and the density parameters are presented. The mechanical properties of the cancellous bone in the mandibular condyle appeared to be highly anisotropic. Obviously, because the specimens of both groups were taken from the same individual, the density parameters did not differ between the two groups. There were no dependencies of mandibular half (left or right condyle) for any of the parameters. However, mechanical properties differed within the condyle, i.e., for the transverse loading group the lateral site of the condyle had a significantly higher E-modulus, ultimate stress and failure energy than the medial site; such a mediolateral difference was not found for the axial loading group.

Pearson's correlation coefficients of the log-transformed mechanical and density parameters are presented in Table 2. Not only high coefficients of correlation among mechanical properties were found, but also between mechanical properties and the apparent density and volume fraction. Only the ultimate strain in the samples from the transverse group did not correlate to the other parameters. The tissue density showed no correlation with any other parameter in either the axial or the transverse group, which is not surprising because of its small standard deviation.

A scatter plot of the E-modulus and the apparent density is shown in Fig. 2. In both the axial and transverse loading groups, the E-modulus depended on the apparent density. The solid line in the figure represents the power relationship E-modulus $= B\rho_{\mathrm{app}}^{A}$,

Table 1
Average of mechanical and density parameters for the different groups

	Axial		Transverse		
	Average	S.D.	Average	S.D.	Paired t-test
	($n=24$)		($n=19$)		
E-modulus (MPa)	431	(217)	127	(92)	[a]
Ultimate stress (MPa)	4.5	(1.9)	1.6	(1.0)	[a]
Ultimate strain (%)	1.65	(0.29)	2.11	(0.46)	[b]
Failure energy (kJ/m^3)	48.89	(21.64)	23.95	(16.59)	[a]
	($n=17$)		($n=16$)		
Tissue density (g/cm^3)	2.146	(0.054)	2.127	(0.045)	
Apparent density (g/cm^3)	0.352	(0.063)	0.336	(0.069)	
Volume fraction (%)	16.4	(3.1)	15.8	(3.3)	

[a] $p<0.001$.
[b] $p<0.01$.

Table 2
Pearson's correlation coefficients and their significance level of log-transformed data

	E-modulus	Ultimate stress	Ultimate strain	Failure energy	Tissue density	Apparent density	Volume fraction
Axial group							
E-modulus	1						
Ultimate stress	0.987[a]	1					
Ultimate strain	0.447[b]	0.453[b]	1				
Failure energy	0.915[a]	0.937[a]	0.723[a]	1			
Tissue density	−0.253	−0.216	0.031	−0.119	1		
Apparent density	0.795[a]	0.809[a]	0.368	0.76[a]	−0.288	1	
Volume fraction	0.793[a]	0.801[a]	0.349	0.743[a]	−0.397	0.993[a]	1
Transverse group							
E-modulus	1						
Ultimate stress	0.974[a]	1					
Ultimate strain	−0.174	−0.017	1				
Failure energy	0.845[a]	0.919[a]	0.366	1			
Tissue density	0.134	0.1	−0.389	−0.057	1		
Apparent density	0.697[c]	0.724[c]	0.314	0.804[a]	−0.275	1	
Volume fraction	0.65[c]	0.68[c]	0.351	0.778[a]	−0.359	0.996[a]	1

[a] $p<0.001$.
[b] $p<0.05$.
[c] $p<0.01$.

where A and B are constants. The relative difference between the two groups is smaller at higher densities.

4. Discussion

4.1. Mechanical anisotropy

It appeared that the mechanical properties of the cancellous bone were highly anisotropic. In axial loading the bone was 3.4 times stiffer and 2.8 times stronger upon failure than in transverse loading. The failure energy was about 2 times higher in transverse loading than in axial loading. The ultimate strain was found to be larger in a direction perpendicular to the plate-like trabeculae, indicating that in the transverse direction the bone can be deformed over a larger distance before it collapses. A direction dependency of ultimate strain was also found by Zysset and Curnier (1996), but not by Chang et al. (1999).

The values for E-modulus and strength we found were considerably larger than the values reported for cancellous bone of the mandibular body (E-modulus: 56.0 MPa, compressive strength: 3.9 MPa; Misch et al., 1999). The difference can probably be ascribed to differences in structure and function. For example, in contrast to the condyle the cancellous bone in the body is surrounded by a thick layer of cortical bone. Our values of the E-modulus for the axial group are in the range found for other bones (proximal tibia: 635 ± 386 MPa ($\pm$ S.D.), Ding et al., 1997; proximal femur: 441 ± 271 MPa, Lotz et al., 1990; acetabulum: 60 ± 48 MPa, Dalstra et al., 1993; vertebral body: 316 ± 227 MPa, Hou et al., 1998).

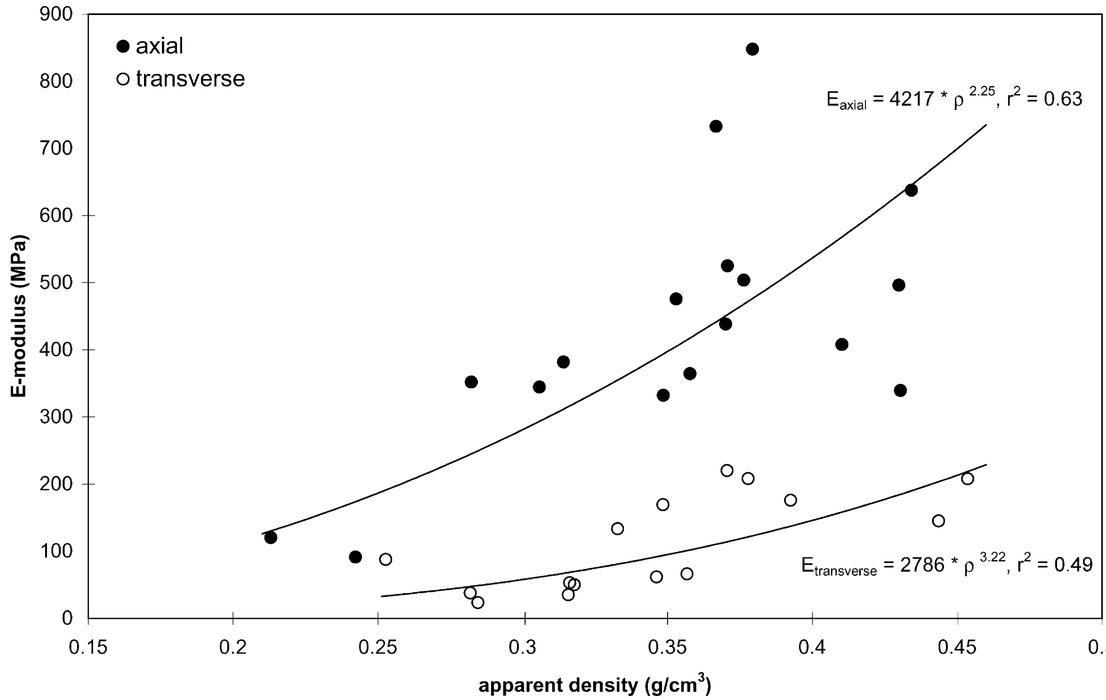

Fig. 2. Scatter plot of E-modulus versus apparent density, filled circles: axial-group, open circles: transverse-group. The fitted line through each group is the power relationship shown in the figure.

Some points should be noted. Firstly, in studying mechanical properties of cylindrical bone specimens a diameter of 7.5 mm and length of 6.5 mm is recommended (Linde et al., 1992). However, we had to limit the diameter to 3.6 mm because of the relatively small size and curved shape of the condyle. The small specimen size could have influenced the measurements, e.g., underestimation of the modulus of elasticity (Linde et al., 1992). To prevent buckling during the mechanical tests the length of the specimen was predetermined to be approximately 5 mm. Due to the specimens size the continuum assumption (Harrigan et al., 1988) is not valid, but at this point no alternative testing methods are available. Further, the compression tests between parallel plates generate systematical and random errors (Keaveny et al., 1997). The mechanical properties are therefore indicative, but the major findings of this study in terms of anisotropy are not invalidated. Secondly, the elastic modulus was determined at 0.6% strain. The elastic modulus might be underestimated as in some specimens the bone already begins to yield at that strain level. However, in literature often 0.6% strain is used to calculate the E-modulus (Linde et al., 1988; Ding et al., 1997). Thirdly, the embalming procedure could have changed the mechanical properties, i.e., a slight increase in stiffness (Linde, 1994). Fourthly, the specimens were taken from relatively old cadavers. Age-related decrease of density and E-modulus (Ding et al., 1997) could be expected. In the present study (data not shown) and that of Hongo et al. (1989a), both examining the human mandibular condyle, no correlation between these parameters and age were found.

4.2. Mechanical properties and density

The bone volume fraction appeared to be in the same range as found in a previous study (Giesen and Van Eijden, 2000). The apparent density, 0.35 g/cm^3, was in the range found for other bone (acetabular bone: 0.20–0.35 g/cm^3, Dalstra et al., 1993; proximal tibia: 0.46 ± 0.12 g/cm^3, Ding et al., 1997; 0.24 ± 0.09 g/cm^3, Carter and Hayes, 1977).

Not only high coefficients of correlation among mechanical properties were found, but also between mechanical properties and the apparent density and volume fraction. Ultimate strain does not correlate with apparent density (Kopperdahl and Keaveny, 1998). This was confirmed in the present study. It implicates that independent of the amount of tissue the bone can deform to a predetermined strain before it collapses. If the bone is subject to larger loads it will adapt and increase its apparent density, allowing the same amount of strain. Ultimate strain and tissue density did not correlate to any of the other parameters investigated.

Acknowledgements

This research was institutionally supported by the Inter-University Research School of Dentistry, through the Academic Centre for Dentistry Amsterdam. The authors would like to thank Anette Milton and Jane Pauli for laboratory assistance.

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