

## Elastic Properties of Human Supraorbital and Mandibular Bone

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**ABSTRACT** Elastic constants, including the elastic modulus, the shear modulus, and Poisson's ratio, were measured on human craniofacial bone specimens obtained from the supraorbital region and the buccal surfaces of the mandibles of unembalmed cadavers. Constants were determined using an ultrasonic wave technique in three directions relative to the surface of each sample: 1) normal, 2) tangential, and 3) longitudinal. Statistical analysis of these elastic constants indicated that significant differences in the relative proportions of elastic properties existed between the regions. Bone from the mandible along its longitudinal axis was stiffer than bone from the supraorbital region. Directional differences in both locations demonstrated that cranial bone was not elastically isotropic. It is suggested that differences in elastic properties correspond to regional differences in function.

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If form and function are related in the skeletons of vertebrates, then it might be expected that bone will be the strongest and most resistant to deformation in the direction in which it is primarily loaded. Likewise, bone that is not heavily loaded or is loaded in multiple directions equally, might exhibit less directionality in resistance to deformation. Despite an abundance of literature describing both the mechanical properties of postcranial bone and in vivo strains produced in postcranial bone during functional activities (for reviews, see Cowin, 1989a,b; Lanyon and Rubin, 1985), few studies have addressed questions of the relationship between loading patterns in the skeleton and the mechanical properties of bone. One reason for this may be that studies of the postcranium have focused largely on the midshafts of long bones, both because of accessibility and because of the thickness of the cortical plates in these regions. Yet, loading patterns in the midshafts of long bones are likely to be more similar than dif-

ferent. Thus little opportunity is provided to contrast the material properties of bone from regions with large variations in loading patterns.

The craniofacial skeleton is ideal for studying material properties of bone from regions that may have large differences in loading. Several studies by Hylander have described in vivo bone strains in the mandible of macaques during mastication and biting (Hylander, 1979a,b, 1985, 1987). Preliminary work in our laboratory also indicates basic similarity in the elastic properties of bone from along the lower border of the mandibular corpus between humans and macaques (Dechow et al., 1989; Nail et al., 1989). More recently, in vivo strain gage studies have been extended to the zygomatic arch, the postorbital bar, and the supraorbital and interorbital regions in macaques and baboons (Hylander et al., 1987a,b, 1989,

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1991a,b, 1992) and African green monkeys (Oyen et al., 1991).

Available data on the elastic properties of bone from the craniofacial skeleton are primarily confined to the mandible and consist of a study of human mandibular bone from 21 individuals (Dechow et al., 1992), data from possibly immature bone from canine mandibles (Ashman et al., 1985), and reports of smaller samples also taken from human mandibles (Ashman and Van Buskirk, 1987; Carter, 1989; Arendts and Sigolotto, 1989, 1990; Rho, 1991). Data on the ultimate strength (Robertson and Smith, 1978) and density (Powell et al., 1973) are available for the mandibles of pigs. Bromage (1992b) has presented information on collagen fibril orientation in macaque mandibles, and Bacon et al. (1980) have presented information on apatite crystal orientation in an edentulous human mandible; both of these features are thought to be important microstructural determinants of osseous material properties (Ascenzi, 1988). Data on the elastic properties and related micromechanical features of supraorbital bone are not available other than preliminary reports of the current investigation (Dechow et al., 1988; Nail et al., 1988), and data on collagen fibril orientation in macaques (Bromage, 1992a), although several studies present data for bone from the cranial vault (Evans and Lissner, 1957; Schröder et al., 1977). Thus comparisons between loading patterns and the elastic properties of bone in the primate craniofacial skeleton are limited by a lack of elastic property data.

In vivo strain gage studies in monkeys (*Macaca fascicularis*) have demonstrated maximum tensile, compressive, and shear strain values along the inferior border of the mandible in the molar region of up to 1,122, -1,442, and 2,564  $\mu\epsilon$  (microstrain), respectively, during molar transducer biting. Similar if not greater values are common in long bones of large experimental animals such as sheep during locomotory activities (Lanyon and Rubin, 1985). Strains similar to those found in the mandible and postcranial bone might be expected in the supraorbital "brow ridge" area during orofacial functions such as mastication. This would be true if bone in

that area develops as a buttress against the transmitted forces of biting and mastication (for a review of arguments for and against this hypothesis, see Ravosa, 1988, 1991). However, strain gage studies have shown that even during peak masticatory and biting activities (Hylander et al., 1987a,b, 1989, 1991a,b, 1992) and during maximum masticatory muscle stimulation in anesthetized monkeys (Oyen, 1987; Oyen et al., 1991) bone strains exhibited in the supraorbital region are less than 200  $\mu\epsilon$  in monkeys.

In vivo studies have not been possible in humans because of their invasive nature; yet available data from artificially loaded human craniofacial skeletons show a similar dichotomy as in monkeys between strain along the corpus of the mandible and in the supraorbital region. Data from Endo (1966, 1970) indicate that the magnitude of bone strain in the supraorbital region of humans is low compared to other regions of the face (Picq and Hylander, 1989). Unfortunately, Endo did not conduct artificial loading experiments on the human mandible, which would enable direct comparisons. However, data from our laboratory (Throckmorton et al., 1992) show values of bone strain along the human mandibular corpus of up to 800  $\mu\epsilon$  in human mandibles loaded with artificial muscle forces of up to 60 kiloponds. The difference in bone strain between the mandibular and supraorbital regions suggests functional differences between these regions. It is likely that bone in the supraorbital region serves functions other than simply absorbing stresses brought on by biting and mastication, since it would appear that bone in this region is overly engineered for this purpose alone (Hylander et al., 1987a,b, 1989, 1991a,b).

Bone is an inhomogenous anisotropic material. However, most data on the elastic properties suggest that cortical bone can be effectively modeled as either an orthotropic or transversely isotropic material (Ashman et al., 1984; Cowin, 1989b; Martin and Burr, 1989). Thus elastic constants vary with direction, although this variation is symmetrical around three mutually perpendicular axes (orthotropy), or elastic constants are identical about two of the three axes (trans-

verse isotropy). Transverse isotropy of cortical bone in the radial and tangential directions especially seems evident in remodeled long bones (Katz et al., 1984). These directional differences in the elastic constants were surmised by many workers in skeletal biology prior to the time when accurate measurement of elastic moduli in bone could be easily made. For instance, Dempster (1967) used so-called split-line patterns to define the direction of "grain" in the skull. These patterns were thought to reflect the directions in which the microstructure of the bone was oriented to resist stress. A study by Ashman et al. (1985) suggested that canine mandibular bone is isotropic. This anomalous result may have resulted from the testing of bone from immature individuals (Ashman and Van Buskirk, 1987). All other data on cranial and mandibular bone indicate directional differences in elastic properties (Arendts and Sigolotto, 1989, 1990; Carter, 1989; Dechow et al., 1992; Rho, 1991).

This study was designed to contrast the elastic properties of bone in an area demonstrating higher strains during normal mastication, such as the mandible, with an area exhibiting lower strain values during functional activities, such as the supraorbital region. First, it was hypothesized that the supraorbital area, which undergoes minimal loading during mastication and biting (see above references), would exhibit lower elastic moduli. Second, it was hypothesized that the greatest differences in directional properties would be found in an area that resisted large loads in consistent directions. Hylander (1979b) has demonstrated that the macaque mandible is primarily bent in a parasagittal plane on the balancing side, while undergoing primarily torsion on the working side during mastication. Strain magnitudes are comparable to those found in some long bones during function (Dechow et al., 1992). Modeling studies of the human mandible (Hart et al., 1992; Koriath et al., 1992a,b) and preliminary studies on artificially loaded human mandibles in our laboratory (Throckmorton et al., 1992) have yielded results that are consistent with findings in monkeys, and, in any case, it is rea-

sonable to propose that basic patterns of mandibular loading are similar in most anthropoids (Hylander, 1988).

## MATERIALS AND METHODS

The present study used specimens of bone removed with striker saws from 20 unembalmed (frozen) whole or partial human heads. The sexes of the individuals were a random mix. The ages were primarily those of older individuals because those specimens were the ones available in the cadaver population. Crania were largely dentate, although two individuals were edentulous. Mandibular bone samples were not taken from the edentulous individuals, as data from several specimens suggest that edentulation renders mandibular bone slightly less dense and less stiff (Carter, 1989). Two supraorbital specimens came from the edentulous individuals. Data from these individuals fell within the range of data from dentate individuals, and thus were included in the study. None of the individuals sampled were known to have died of any primary bone diseases.

Previous studies on the effects of storing bone samples in preservative media such as formalin, though largely inconclusive, suggest the possibility that the collagen fibers comprising the organic matrix of bone might be altered thus affecting the elastic properties of the bone (Reilly and Burstein, 1974). Accordingly, samples were stored in a solution consisting of 95% ethanol and isotonic saline in equal proportions, a medium that has been shown to maintain the elastic properties of cortical bone for several weeks (Ashman et al., 1984).

Bone specimens were prepared for testing from each of the following locations (Fig. 1): 1) superior to the midline of the orbit, and 2) from the buccal surface of the lower border of the mandibular corpus inferior to the second molar. Sample sizes at each site (Table 1) varied depending on the condition of the crania from which the bone was obtained (crania had been used as practice specimens for jaw surgeries before the harvesting of the bone specimens). Samples of cortical bone were machined to 5 × 5 mm squares. The

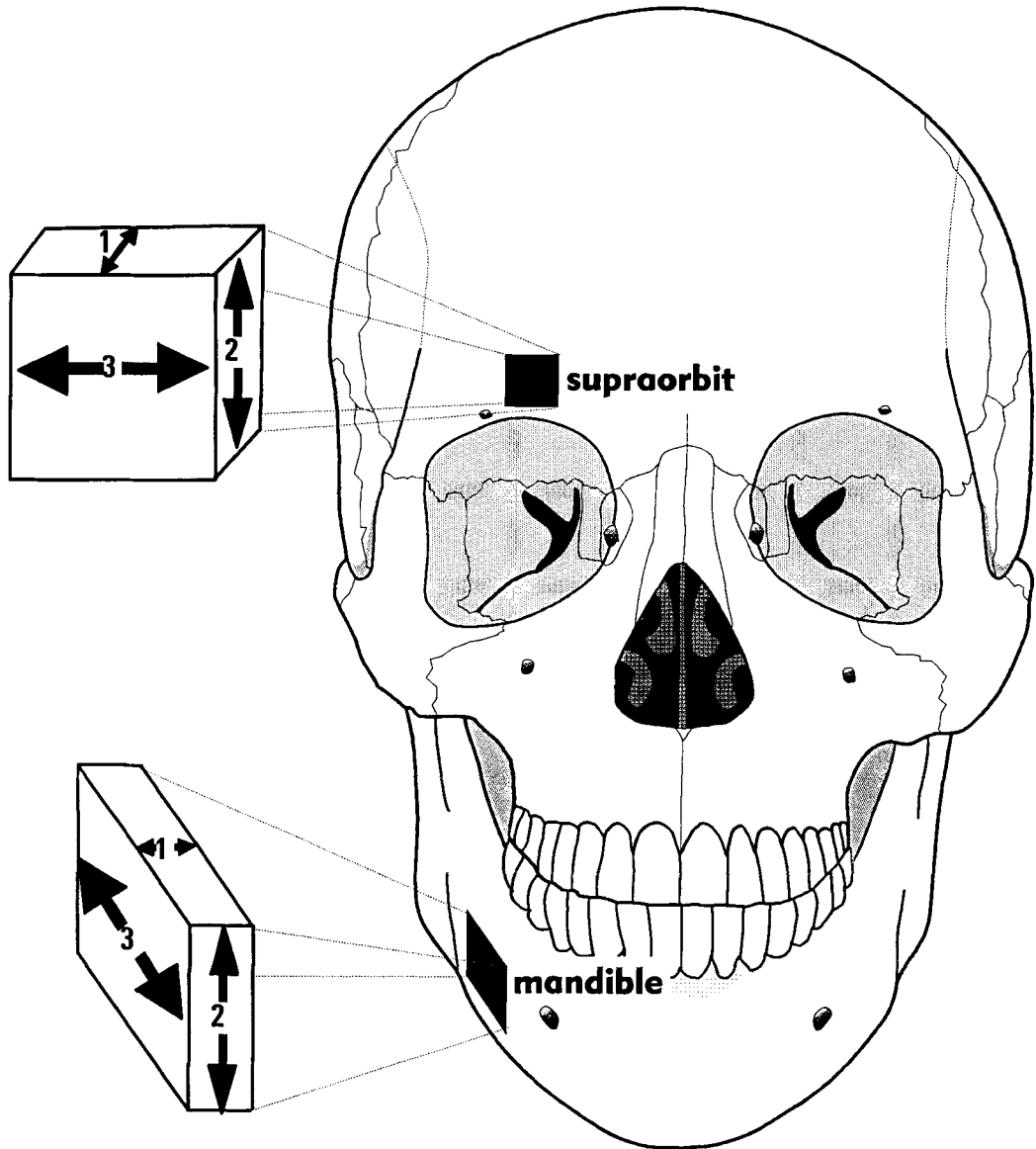


Fig. 1. Areas and directions for bone sample sites. Bone samples, approximately 5 mm × 5 mm × 3 mm were taken from the mandible and supraorbit at the sites indicated. The 1 direction was normal to the surface of the bone. The 2 direction was tangential or superoinferior along the bone surface. The 3 direction was longitudinal or axial along the bone surface.

thickness of the specimens was usually limited to 2–3 mm. All specimens were labeled with an arrow to indicate orientation. Densities for each sample were then determined using Archimedes Principle of Buoyancy (Ashman, 1989).

TABLE 1. Bone density

	Mean	SD
Mandible (N = 17)	1.768	0.115
Supraorbit (N = 15)	1.591	0.177

<sup>1</sup> Means are significantly different at  $P < .005$ ,  $T = 3.2$ . All values are in  $\text{g/cm}^3$ .

Samples were tested with a pulse transmission technique in three mutually perpendicular directions, using methods described by Ashman et al. (1984, 1987) and Ashman and Van Buskirk (1987). The ultrasonic waves were generated by piezoelectric transducers resonating at 2.25 MHz. On each sample, the directions were labeled as follows: 1 represented a direction normal (radial) to the bone surface, 2 was tangential to the bone surface (directed superoinferiorly), and 3 (the reference axis) was longitudinal to the bone surface (parallel to the interpupillary line in the supraorbital region and parallel to the longitudinal axis in the mandible) (Fig. 1).

The longitudinal or reference direction was verified following histological examination of samples from each site, including ground and decalcified sections. Decalcified bone was examined by several serial sections of the face of the bone cubes in each of the three planes. The reference axis was roughly parallel to the orientation of the majority of haversian canals, although further research is necessary for a more precise determination, especially in the supraorbital area. In the mandibular corpus, Bromage (1992b) has verified that haversian canals as well as most collagen fibrils are oriented parallel to the long axis. Bacon et al. (1980) have demonstrated that apatite crystals are also primarily oriented in this direction in the corpus.

Calculations for determining elastic properties from the minimum number of measurements require a prior assumption of orthotropy. This is not a difficult assumption for bone in the normal direction; however, in the longitudinal and tangential directions, some prior estimate must be made of the primary orientation of the material (orientation of the haversian systems, collagen, or apatite crystals) (for further discussion, see Ashman et al., 1984; Ascenzi, 1988; Carter, 1989; Cowin, 1989b; Martin and Burr, 1989). In the mandible, Carter (1989) has empirically verified a longitudinal orientation identical to the one used here. This was done by cutting circles of bone (instead of cubes) from the cortical bone of the mandible. Ultrasonic waves were then passed through the bone in multiple directions par-

allel to the cortical surface in order to find the direction that allowed the highest velocities. Below the second molar on the lateral cortex, this direction was parallel to the long axis of the lower border of the mandible. In the supraorbital area, the question of primary direction of material is more problematic. We used a technique similar to that of Carter (1989) as described by Ashman et al. (1984). By cutting the corners from the cubes in the supraorbital area, we were able to measure ultrasonic velocities every 45° in the plane parallel with the cortical surface. On most specimens, velocities were similar in all directions, indicating that the bone was transversely isotropic in the plane parallel to its surface. This transverse isotropy is demonstrated in the technical constants (see Results).

The measurement procedure involved using two mounted piezoelectric transducers to propagate longitudinal and transverse ultrasonic waves through the bone samples in the directions being tested. The time delay of wave propagation was then read directly from an oscilloscope connected to the transducer mount. The time delay, width, and density of the bone samples were then used to generate a matrix of elastic coefficients, or "C" matrix, defined by Hooke's law. Technical elastic constants were then computed. These computational techniques are described in numerous discussions in the literature (Ashman, 1982; Ashman et al., 1984; Ashman and Van Buskirk, 1987; Carter, 1989).

The technical elastic constants determined in this investigation included the elastic modulus, shear or rigidity modulus, and Poisson's ratio. The significance of the elastic constants is described in most textbooks of mechanics (see, for example, Beer and Johnston, 1981; or, for a simpler explanation, Gordon, 1978; or for an explanation directly related to bone, Cowin, 1989c). The elastic constants quantify the relationship between a load (stress) placed on a structure and the resulting deformation of that structure (strain), within its elastic range. As stress on a structure is increased beyond its elastic range, the structure will undergo plastic (irreversible) deformation and failure. The load required for failure is the ulti-

mate strength of the material. Elastic constants and ultimate strength can be related in bone. For instance, in the mandible, preliminary studies in our laboratory (Tipton et al., 1990) have found that cortical bone is most resistant to deformation (stiffest) in the direction in which it is also the most strong. However, if a wider variety of bones are examined, there is an overall inverse relationship between stiffness and strength relating to the degree of mineralization (Currey, 1979, 1984). Current theories suggest that strain and strain rate are important determinants in skeletal modeling (see Martin and Burr, 1989, for extensive discussion). Stiffness of bone then is of great importance as an indication of the relationship between load (stress) and deformation (strain).

The elastic modulus is a measure of the ability of a structure to resist deformation in the direction of the applied load. It is defined by Hooke's law as:

$$E = \frac{\sigma}{\epsilon} \quad (1)$$

where  $E$  is the elastic modulus,  $\sigma$  is stress (force per unit area), and  $\epsilon$  is strain (change in length/original length). Since strain is a dimensionless ratio, the elastic modulus is also given in units of stress, or force per unit area. Here all elastic and strain moduli are given in gigapascals (GPa), which are Newtons per meter<sup>2</sup>  $\times 10^9$ .

The shear or rigidity modulus is a measure of the ability of a structure to resist shear stresses in a given plane. It is defined by Hooke's law for shearing stress and strain as:

$$G = \frac{\tau}{\gamma} \quad (2)$$

where  $G$  is the shear modulus,  $\tau$  is the shear stress (force per unit area of the cross-section in the plane of shear),  $\gamma$  is the shear strain (change in angular dimensions, usually measured in radians). Shear strain can be imagined as follows: a rectangle undergo-

ing shear deforms to the shape of a parallelogram. The change in angle at the corners of the rectangle is the shear strain. Because shear strain is dimensionless, the shear modulus, like the elastic modulus, is given in units of stress, or force per unit area. For most cases, the shear modulus  $G$  tends to be  $\frac{1}{3}$  to  $\frac{1}{2}$  of the value of the elastic modulus  $E$ .

Poisson's ratio is a measure of the ability of a structure to resist deformation in a direction perpendicular to that of the applied load. For example, if a cube is compressed, it will not only be reduced slightly in dimension in the direction in which it is compressed (primary strain), but it will also deform in the midsection, at right angles to the direction of compression (secondary strain). Poisson's ratio is defined as:

$$\nu = \frac{\epsilon_y}{\epsilon_x} \quad (3)$$

where  $\epsilon_y$  is the secondary strain and  $\epsilon_x$  is the primary strain. Poisson's ratio, as the ratio of two strains, which are dimensionless quantities, is also dimensionless.

Because bone is an anisotropic material, elastic constants vary with direction. In this study, elastic moduli  $E$  are followed by a subscript indicating direction, as defined in Figure 1. Shear moduli are followed by a double subscript indicating the plane of shear. Poisson's ratios are followed by a double subscript in which the first subscript indicates the direction of the primary strain and the second subscript indicates the direction of the secondary strain. (For explanations of the formulae of the technical elastic constants in three dimensions, see Ashman et al., 1984; Cowin, 1989c; or Martin and Burr, 1989.)

Because computational techniques were involved in deriving the elastic constants and because sample sizes were not large, care was taken in the implementation of statistical techniques for hypothesis testing. Normal probability plots, which were generated for each variable by location, suggested that parametric statistics were appropriate for the testing of hypotheses. One-way analysis of variance was used to test for signifi-

TABLE 2. Elastic modulus<sup>1</sup>

	Mandible (M) (N = 17)		Supraorbit (S) (N = 14)		SIG
	Mean	SD	Mean	SD	
E <sub>1</sub>	11.3	2.4	10.9	3.1	NS
E <sub>2</sub>	13.8	2.8	15.2	4.5	NS
E <sub>3</sub>	19.4	4.0	15.2	3.5	M > S
SIG	E <sub>3</sub> > E <sub>1</sub> E <sub>3</sub> > E <sub>2</sub>		E <sub>2</sub> > E <sub>1</sub> E <sub>3</sub> > E <sub>1</sub>		

<sup>1</sup>Analysis of variance indicated significant differences among bone directions ( $F = 25.2, P < .001$ ) and significant interactive effects ( $F = 5.4, P < .01$ ), such that elastic moduli increase in the mandible from E<sub>1</sub> to E<sub>3</sub>, but not in the supraorbital area. Differences, which were determined with posthoc Tukey tests to be significant at or below  $P < 0.05$ , are given under SIG at the end of each row and the bottom of each column. E<sub>1</sub> is the elastic modulus in a direction normal or radial to the surface of the bone; E<sub>2</sub> is the elastic modulus tangential or superoinferior along the bone surface; and E<sub>3</sub> is the elastic modulus longitudinal along the bone surface. These directions for the two sites are illustrated in Figure 1. All values are in GPa.

cant difference in bone density among locations. Two-way analysis of variance was used to test for significant differences between directions and locations for the elastic moduli, shear moduli, and Poisson's ratios. Significant differences between individual cells were determined with posthoc Tukey tests.

## RESULTS

A comparison of the average bone densities (Table 1) revealed a significant difference between the two regions. Mandibular bone (1.768 g/cm<sup>3</sup>) was on average more dense than supraorbital bone (1.591 g/cm<sup>3</sup>).

The most notable significant differences in elastic moduli were between the longitudinal direction and the other two directions tested in the mandible, and between the longitudinal direction in the mandible and that direction in the supraorbital region (Table 2). Moduli in the mandible were significantly larger in the longitudinal direction than in the normal and tangential directions, which were not significantly different from each other. The magnitudes of the elastic moduli in the normal and tangential directions averaged 58% and 71%, respectively, of the magnitude of the elastic modulus along the long axis (longitudinal direction).

In the supraorbital area, the largest average elastic moduli, found in the tangential and longitudinal directions, were signifi-

TABLE 3. Shear modulus<sup>1</sup>

	Mandible (M) (N = 17)		Supraorbit (S) (N = 14)		SIG
	Mean	SD	Mean	SD	
G <sub>12</sub>	4.5	1.0	3.9	1.3	NS
G <sub>13</sub>	5.2	1.0	3.9	1.1	M > S
G <sub>23</sub>	6.2	0.7	5.2	1.1	NS
SIG	G <sub>23</sub> > G <sub>12</sub>		G <sub>23</sub> > G <sub>12</sub> G <sub>23</sub> > G <sub>13</sub>		

<sup>1</sup>Analysis of variance indicated significant differences among bone locations ( $F = 20.0, P < .001$ ) and directions ( $F = 17.7, P < .001$ ). See notes following Table 2 for discussion of posthoc tests. All values are in GPa.

cantly less than the largest elastic moduli (in the longitudinal direction) in the mandible. On average the supraorbital values were 78% of that along the lower border of the mandible. Additional significant differences were found in the supraorbital region between longitudinal and tangential directions and the normal direction. The average modulus in the normal direction was 72% of those in the other directions. This difference was less pronounced than a similar difference between longitudinal and normal directions in the mandible.

Significant differences in shear moduli were found between the two regions and in different directions (Table 3). The magnitudes of moduli were greatest for the mandible. This difference was only significant for G<sub>13</sub>, indicating that the mandible, compared to the supraorbital area, is more resistant to shear in a plane formed by the tangential and normal axes. Significant differences in shear moduli among some directions at each region were also noted. In the mandible, the largest average modulus was found in the G<sub>23</sub> plane, indicating that the mandible is most resistant to shear in a plane constructed of the longitudinal and tangential axes. The least resistance to shear was found in a plane constructed of the normal and tangential axes. In the supraorbital region, the bone was also most resistant to shear in a plane formed by the longitudinal and tangential axes, and significantly less in the remaining two planes perpendicular to the first.

While an examination of Poisson's ratio revealed no significant differences among regions, one significant difference was found

TABLE 4. Poisson's ratio<sup>1</sup>

	Mandible (M) (N = 17)		Supraorbit (S) (N = 14)		SIG
	Mean	SD	Mean	SD	
V <sub>12</sub>	.274	.166	.278	.087	NS
V <sub>13</sub>	.237	.125	.264	.113	NS
V <sub>21</sub>	.317	.168	.376	.093	NS
V <sub>23</sub>	.273	.080	.229	.048	NS
V <sub>31</sub>	.405	.206	.357	.139	NS
V <sub>32</sub>	.376	.073	.244	.088	NS
SIG	V <sub>31</sub> > V <sub>13</sub>		NS		

<sup>1</sup>Analysis of variance indicated significant differences among directions ( $F = 5.5, P < .001$ ). See notes following Table 2 for discussion of posthoc tests. Note that Poisson's ratio is dimensionless and therefore does not have a unit of measurement.

to exist among directions at the mandibular site (Table 4).

### DISCUSSION

The results support the hypotheses mentioned earlier in the text that 1) bone from the mandible is stiffer than bone from the supraorbital area, and 2) bone from the lower border of the mandible exhibits greater directionality in material properties than bone from the supraorbital region. These hypotheses are linked in that bone tissue from the mandible was found to be stiffer than bone from the supraorbital region in the longitudinal direction, but not in the remaining two directions, resulting in greater directionality in the mandibular bone tissue.

Our data show significant differences in elastic properties between directions in both the supraorbital region and the lower border of the mandibular corpus. However, these differences were greatest in the mandible, where the elastic modulus in the longitudinal direction was greater than in the tangential or normal directions. In the supraorbital region, bone material was equally stiff in both the tangential and longitudinal directions. The average value in these later directions was also similar to mandibular bone in the tangential direction. In both regions, the bone material was least stiff in the normal direction; also values for the normal direction were equivalent for both regions.

The results of this study suggest a relationship between skeletal function and the elastic properties of bone. Several recent studies have demonstrated how macroscopic

features of mandibular structure, such as the cross-sectional shape of the corpus and the thickness of the cortical plates, are adaptations to counter incisal and masticatory loads in recent and fossil primates (Hylander, 1979a, 1988; Demes et al., 1984; Daegling and Grine, 1991). Other studies indicate that supraorbital bone is overdeveloped to serve solely as a support for masticatory and biting loads (Hylander et al., 1987a,b, 1989, 1991a,b, 1992). Here we ask if functional relationships are found in the microscopic structure of bone as evident in the resulting elastic properties. In what ways, if any, are the patterns of elastic properties in the craniofacial skeleton optimal for resisting loads induced during incision and mastication? Conversely, we can ask if patterns in elastic properties are influenced by other constraints placed on bone tissues, such as the mechanisms of bone growth, or the maintenance of osseous tissues through secondary bone formation. We will primarily address the first question: are the patterns of elastic properties in the mandibular corpus and supraorbital region optimal for resisting masticatory loads? In addition, we will consider some evidence that answers to the second question may place limitations on the ways in which bone may be configured to resist stress, and on the potential of bone to adapt to altered functions.

### Mandibular corpus

The finding of greater directionality of material properties in the mandible is interesting considering Hylander's (1979a,b,c, 1981, 1984, 1985, 1987, 1988) theories of loading patterns in the mandible during function, as we have also discussed elsewhere (Dechow et al., 1992). Hylander's data suggest that during incisor biting in primates the mandible is primarily bent parasagittally on both sides. The lower border of the ramus is also everted because the resultant masticatory muscle force is located lateral to the mandible. This results in a torsion of the mandibular corpora about their longitudinal axes. During mastication, the mandibular corpus on the balancing side is bent parasagittally, twisted about its long axis, dorsoventrally sheared, and bent in the transverse plane. On the working side, the

corpus is strongly twisted about its long axis and dorsoventrally sheared. Parasagittal bending would be a loading regime of lesser importance on the working side compared to the balancing side.

Bone in the lower border of the mandibular corpus is primarily resistant to deformation in the same direction in which Hylander suggests that the corpus is loaded in compression during parasagittal and lateral transverse bending. Parasagittal bending would place the lower border of the mandible in compression. Lateral transverse bending would place the lateral cortex in compression. The direction of both these compressive loads is longitudinal, which corresponds to the direction of greatest measured stiffness.

Less obvious is how this pattern may resist torsional and shearing loads. Here there are several considerations: 1) How can the information on mandibular elastic properties be used to reassess the results of Hylander's (1979b, 1981, 1984, 1985) experiments? Does this reassessment alter our understanding of the relative importance of torsion as a loading regime in mandibular function in mastication and biting? 2) If torsion and parasagittal bending are the most important loading regimes in the mandible, what elastic properties might we expect to resist these loads? We will discuss each of these questions in turn.

#### *Torsion and shear*

Substantial theoretical considerations attest to the importance of torsion in mandibular loading, especially on the working side during mastication (Hylander, 1979b,c, 1981, 1984, 1985, 1987, 1988; Demes et al., 1984). Variable ability to resist torsion is reflected in the shape of primate mandibles (Hylander, 1979a, 1988; Smith, 1983; Bouvier, 1986a,b; Demes et al., 1984; Daegling, 1989; Daegling and Grine, 1991). Experimental evidence for mandibular torsion during mastication and incision in anthropoids derives from in vivo strain gage experiments in macaques (Hylander, 1979b, 1981, 1984). Gradients of strain along the facial aspect of the symphysis indicate twisting of corpora during mastication (Hylander, 1984). Bone strain along the lower border of the corpus

during mastication shows a different pattern between the working and balancing sides. Hylander (1979b, 1981) argues that the difference can be explained by a greater amount of torsion on the working side compared to the balancing side, coupled with a greater amount of parasagittal bending on the balancing side. Hylander (1979b, p. 282) explains expected strain patterns along lower border of the corpus during parasagittal bending for the maximum principal strain (which in this case is tensile strain and is designated as  $\epsilon_1$ ) and minimum principal strain (which is compressive strain and is designated as  $\epsilon_2$ ) as follows:

If the mandibular corpus were only bent in the sagittal plane during the power stroke, the following situation would take place: (1) the direction of  $\epsilon_2$  (compression) along its lower border would be horizontally positioned; (2) the direction of  $\epsilon_1$  (tension) along this same site would be vertically positioned, since  $\epsilon_2$  is always perpendicular to  $\epsilon_1$ ; (3) the absolute value of  $\epsilon_2$  would be larger than  $\epsilon_2 \dots$

Regarding torsion, Hylander (1979b, p. 283) argues:

Twisting would tend to evert the lower border of the mandible and invert the alveolar process, since the masticatory muscle force resultant must be positioned lateral to the long axis of the mandibular corpus during biting. Pure twisting (1) would cause  $\epsilon_1$  to be directed upwards and backwards along the lateral surface of the mandibular corpus at an angle of approximately 45° relative to its long axis, and (2) the magnitude of  $\epsilon_1$  and  $\epsilon_2$  would be the same.

Hylander's (1979b, 1981) results show that during mastication 1) the average direction of  $\epsilon_1$  on the balancing side is close to vertical in a number of experiments, and is closer to vertical than that on the working side in the majority of experiments. This results in  $\epsilon_2$  being parallel to, or closest to horizontal, on the balancing side. 2)  $\epsilon_1$  on the working side is directed upwards and backwards along the lateral surface of the mandibular corpus at an angle of approximately 45° relative to its long axis in a number of experiments, and is closer to this position than that on the balancing side in the majority of experiments. This results in  $\epsilon_2$  being directed downward and backwards along the lateral

surface of the mandibular corpus at an angle of approximately 45° relative to its long axis or closest to this position on the working side. 3)  $\epsilon_1$  and  $\epsilon_2$  have similar magnitudes in the majority of experiments on both working and balancing sides. Hylander explains these results as indicating the predominance of parasagittal bending on the balancing side, and torsion on the working side. Bending is also thought to be evident on the working side but of lesser magnitude than torsion. Likewise, torsion is thought to be evident on the balancing side, but of lesser magnitude than bending. Dorsoventral shear is thought not to be important along the lower border of the mandible, but may concentrate its effects in the alveolar region at the bite point.

A problem in the interpretation of the results from Hylander's experiments was that the elastic properties of the macaque mandible were not known and were thus not used in the calculations. Even though the interpretations are largely qualitative, they are based on an assumption of isotropy in the mandible, with the resulting corollary that the directions of primary strain are equivalent to the directions of primary stress. Our results from the human mandible (Dechow et al., 1992 and the current study) indicate that on average  $E_3$  is approximately 40% larger than  $E_2$ .<sup>1</sup> Preliminary studies in our laboratory on the macaque mandible (Dechow et al., 1989; Nail et al., 1989) suggest that the relative differences between  $E_2$  and  $E_3$  may be even larger. These differences in elastic moduli by direction would result in dissimilarities between the directions of principal strain and the directions of principal stress (Carter, 1978). Cowin and Hart (1990) demonstrate that these dissimilarities may be as large as 45° in anisotropic materials.

How would differences between  $E_2$  and  $E_3$  extend the results of Hylander's experi-

ments? It is not our purpose here to give a rigorous explanation of the differences. We will present this elsewhere with a formal discussion of our data from macaque mandibles (Dechow et al., 1989; Nail et al., 1989). However a qualitative discussion allows some reassessment of the importance of torsion in loading the lower border of the human mandible. Assume for this discussion that  $E_3$  is greater than the value of  $E_2$ .

If strain gage experiments indicate that  $\epsilon_1$  is oriented vertically and  $\epsilon_2$  is oriented horizontally (in other words, if they correspond with the fixed directions of  $E_2$  and  $E_3$ ), there should be no difference in the directions of the principal strains and stresses. However, a comparison of the magnitudes of the strains in the two directions will be misleading. For example, if  $E_3$  is twice that of  $E_2$ , then similar absolute values of  $\epsilon_1$  and  $\epsilon_2$  will indicate that the absolute value of  $\sigma_2$  (minimum principal stress) is actually twice that of  $\sigma_1$  (maximum principal stress) (see Equation 1).

Directions of principal strains and stresses will also differ depending on the orientation of  $\epsilon_1$  and  $\epsilon_2$ . If  $\epsilon_1$  is closer to being directed upwards and backwards along the lateral surface of the mandibular corpus at an angle of 45° or less relative to its long axis, and  $\epsilon_2$  is closer to being directed downwards and backwards along the lateral surface of the mandibular corpus at an angle of 45° or less relative to its long axis, then the actual direction of  $\sigma_1$  will be oriented more toward the vertical than the direction of the  $\epsilon_1$ . Likewise, the actual direction of  $\sigma_2$  will be oriented more toward the horizontal than the direction of the  $\epsilon_2$ . The magnitude of  $\sigma_2$  will also be larger relative to  $\sigma_1$ , compared to the relationship between  $\epsilon_2$  and  $\epsilon_1$ .

How do these differences between principal strains and stresses affect the interpretation of the results of Hylander's experiments? Based on Hylander's (1979b, 1981) arguments, these extended results would strengthen the assessment of the importance of bending along the lower border of the corpus, and deemphasize the importance of torsion during mastication and incision. This is not to say that both these loading regimes are not important in mandibular loading, but rather to suggest

<sup>1</sup>Note that subscript terms do not correspond between values of the elastic modulus ( $E$ ) and the principal strains ( $\epsilon$ ). Subscript terms for the elastic modulus represent fixed directions relative to the lower border of the mandible, while subscript terms for the principal strains ( $\epsilon$ ) represent maximum and minimum strains which vary in direction depending on the nature of the load on the structure. For further explanation, see the Materials and Methods sections of this paper and Hylander (1979b).

that bending may be of greater importance in producing strains on the working side during mastication than the strain data previously indicated. Also, as Hylander has suggested, the importance of both these loading regimes should shift with the position of the bite point. This suggests that bending will be an important component throughout much of the working side corpus in positions both anterior and posterior to the bite point. A related possibility is that the macrostructure of the mandible is better configured to resist torsional stresses compared to bending stresses (Hylander, 1979a, 1988; Demes et al., 1984; Daegling, 1989; Daegling and Grine, 1991). This would enhance measured strains in directions corresponding to those that result from parasagittal bending.

#### *Elastic properties and mandibular loads*

What elastic properties would be optimal for resisting mandibular loads? Based on the above discussion, we would expect that bending and torsion in varying proportions would be responsible for loading at the lower border of the mandibular corpus. Primary stiffness in the longitudinal direction would optimally resist bending loads. Optimal directions of primary stiffness for resisting torsional loads would require similar elastic moduli in both longitudinal and tangential directions, or transverse isotropy in the plane parallel to the cortical plate. This would allow optimal resistance for similar magnitudes of compression and tension in all directions, especially in the case of torsion, at 45° to the long axis of the mandible. If the primary direction of stiffness were at some angle to the long axis of the mandible so as to increase the ability to resist compression during torsion, this would not necessarily strengthen the mandible for resisting tension (at 90° to the direction of the compression), unless the bone approached transverse isotropy in the plane parallel to the cortical plate.

Comparisons of optimal properties for resisting torsion suggest that the elastic properties in the mandible are not optimally oriented to resist torsion alone. However, if loads on the mandible are usually some com-

ination of bending and torsion, then we would expect an optimal configuration of material properties that is an average of the conditions for resisting these loads. We might then expect that the bone is more stiff longitudinally than tangentially and that the direction of primary stiffness is longitudinal. We would also expect that bone has significant resistance to deformation in the tangential direction to counter torsional loads. It would be interesting in further experimentation to compare tangential elastic moduli in similar bones in which torsional stresses are different, as a way to assess variability and adaptability in this property. It would also be interesting to assess the impact of transverse isotropy in the plane parallel to the surface of the bone. What constraints would this imply for the development and adaptation of the cortical plate? How large might the resistance to deformation be in such cortices without placing other limitations on the bone?

Another consideration is the shear modulus of the material. The ability to resist torsion or bending would be optimally resisted by a large shear modulus in the plane formed by the longitudinal and tangential axes. As we have shown, this plane does have the largest shear modulus for the mandible. The magnitude of this modulus is directly related to the magnitude of the elastic modulus in either the longitudinal or tangential directions. In this way, the high longitudinal modulus, by its effects on the shear modulus, would stiffen the mandible for resisting torsion. Koriath et al. (1992a, and personal communication), in a preliminary investigation, used a finite element model of the human mandible to predict internal loads and deformations. They showed that variations in the shear moduli in the plane parallel to the surface of the bone produced the largest deviations in the predicted directions of primary strain. The techniques of finite element modeling of the mandible (Hart et al., 1992; Koriath et al., 1992a,b) may be a better way to predict optimal orientations of material properties, because, as Daegling (1989) has pointed out, ellipse models of the mandible "do not predict the biomechanical properties of corpus cross-sectional geometry in an accurate or reliable

manner." These techniques may allow a resolution to this question in future research.

Finally, it is important to note that some features of the elastic properties of bone might be constrained by the remodeling process. Katz et al. (1984) (see also discussion in Martin and Burr, 1989) have presented evidence that one impact of haversian bone formation is a shift of cortical bone from an orthotropic to a transversely isotropic material. The transverse isotropy would be about the two axes, which are distinct from the primary axis of the material. In the case of long bones this would be about the radial and tangential axes. Our study has demonstrated transverse isotropy about these axes in the mandible. It is possible that the elastic properties we have found in the mandible of individuals, which are primarily from an older cadaver population, reflect remodeling of the cortical bone. In the case of extensive remodeling, it may be that if variations in elastic properties of bone are correlated with function, that these variations are found primarily along the longitudinal axis. It is suggestive that the stiffest region along the mandibular corpus is at the lower border inferior to the canine/third premolar (Dechow et al., 1992); this region also has the highest resistance to torsion and is the region where torsional stresses are suspected to change direction during function (Demes et al., 1984).

### Supraorbital region

The central purpose of this study is to contrast the elastic properties of cortical bone in the mandibular corpus and supraorbital region and ask how their elastic properties reflect their functions. Numerous studies have examined the elastic properties of long bones that are heavily stressed primarily in one direction, such as the femur (for summary, see Cowin, 1989a,b). The mandible has many similarities to the femoral mid-shaft in its elastic properties. Both bones are most stiff in their longitudinal orientation and their elastic moduli suggest a transverse isotropy in the tangential and radial directions. This similarity has led Carter (1989) to suggest that the mandible in many ways is like "a long bone bent in the shape of a parabola," although the mandible does

maintain distinct features based on its own geometry (Carter, 1989; Dechow et al., 1992). The similarity between the elastic properties of the mandible and femur contrasts with those of the supraorbital region, where our data indicate a transverse isotropy in the longitudinal and tangential directions, and lower absolute values of elastic moduli. Functionally, the supraorbital region differs from the mandible and femur in that it experiences lower magnitudes of strain in multiple directions during function (Endo, 1966, 1970; Hylander et al., 1987a,b, 1989, 1991a,b, 1992; Oyen, 1987; Oyen et al., 1991).

Early studies of the supraorbital region attempted to reproduce the static condition of biting in human crania and record the strains produced (Endo, 1966, 1970). Strains were thought to support theories that the browridge can be modeled as a beam that is acted on by an intense bending moment, especially at its center, which causes it to be deformed nearly parallel to the vertical direction. This bending would be associated with the lateral portions of the supraorbital region being pulled downward by the action of the masseter and temporalis while the central "glabellar" region is pushed upward by the bite force (for discussion of the development of thought in this area, see Picq and Hylander, 1989). It was thought that the high cross-section of bone in this region exists to resist this intense bending moment (Endo, 1966). However, as discussed by Picq and Hylander (1989) based on data from Endo (1966), strains recorded throughout the human supraorbital region are quite low compared to strains recorded in other portions of the facial skeleton, especially the zygoma and maxilla. Thus, there is little support from strain gage studies for the idea that the supraorbit is a highly stressed area during biting and therefore little rationale for theories that link its morphology to the countering of heavy masticatory and biting loads (Picq and Hylander, 1989).

As stated above, elastic properties determined in this study indicate that above the orbit, the bony tissue in the browridge is equally resistant to deformation both along an axis parallel to the interpupillary line

(longitudinal direction) and in an inferosuperior (tangential) direction. Elastic moduli in the remaining direction, normal to the surface of the bone, are 72% of these average values. This suggests that the bone tissue in the supraorbital region is transversely isotropic in the coronal plane. Thus bone in this region might be equally well suited to resist loads in any direction parallel to its surface. This situation differs markedly from that in the mandible where the surface of the bone is at right angles to that in the supraorbital region. In the mandible, the possible transverse isotropy is perpendicular to the surface of the bone and in the directions in which the bone is least able to resist deformation.

Because of the transverse isotropy in the plane parallel to the surface of the bone, directions of principal strains and stresses in the supraorbital region are identical. Descriptions of bone strain in this region and the inference of loading patterns (Hylander et al., 1987a,b, 1989, 1991a,b) do not require further explication based on elastic properties, at least in the area directly above the human orbit.

The magnitudes of the supraorbital elastic moduli in all directions are generally similar to those reported for bone tissue from the shafts of long bones in the normal and tangential directions. For example, Cowin (1989b) summarizes values from the literature of moduli measured with ultrasonic methods. He reports values of elastic moduli ranging from 6.9 GPa for human tibiae to 18.8 GPa for human femora, with most values ranging from 10.0–13.0 GPa. The values for the longitudinal direction in the mandible are larger and are similar to those for the longitudinal direction in human long bones (Cowin, 1989b; Dechow et al., 1992). Cowin (1989b) reports average elastic moduli ranging from 17.0 GPa–27.4 GPa, with most values ranging from 18.0–20.0 GPa. These data certainly indicate that the supraorbital area in its elastic properties is not as well adapted to resist loads as the mandible or as long bones of the body along their longitudinal axis. One study in the literature (Schröder et al., 1977) has reported elastic moduli from the cranial vault using a mechanical testing technique. However, the

values of the moduli are two orders of magnitude less than those of most other mammalian bone, suggesting that these studies should be repeated. Our data are similar to the elastic properties of other mammalian bone and are consistent with the idea that the browridge is structured to resist some degree of loading in varying directions parallel with its surface.

### **Bone adaptation in the craniofacial region**

Of central interest here is the question of the adaptational potential of bone. It is known that bone in an organism can adapt by modeling over time to increased loads (elevated strain) (Burr et al., 1989a,b). Under certain conditions, this will lead to increased thickness of the cortical plate or increased bone mass, resulting in a stronger architectural member (Lanyon and Rubin, 1985). Whether bone can also adapt in the short term by shifts in material properties or by changes in the direction in which it is most resistant to deformation is an open question. Lanyon and Rubin (1985, p. 11) have argued because of findings by Woo et al. (1981) that "internal bone remodeling is not an adaptive response to improve the material properties of bone tissue," although it may increase the fatigue life of the skeletal structure. However, bone modeling on periosteal and endosteal surfaces does have the potential to form lamellar bone or woven bone (Ascenzi, 1988; Burr et al., 1989b; Martin and Burr, 1989). These types of bone have variations in microstructural elements that correlate with material properties, such as collagen fiber or apatite crystal orientation. Thus formation of bone through modeling may allow some changes in the material properties of the cortical plate as a whole.

Bundy (1989, p. 208) has argued that "because of the very complex nature of bone microstructure, no consensus has emerged as to what the salient factors of bone microstructure actually are." Important features that have been found to correlate with the material properties of bone include porosity (or bone volume fraction) (Schaffler and Burr, 1988), collagen fiber orientation, structure of lamellae (Ascenzi, 1988), apatite crystal orientation (Sasaki et al., 1989),

haversian system orientation, and other aspects of the microstructural organization of bone (for further discussion, see Martin and Burr, 1989). Given this lack of understanding of the details of the relationship between structure and function in bone, the question of adaptation of bone microstructure and its effect on the overall function and architecture of a skeletal member is even more problematic. It is possible that elastic properties in bone have adapted only in a phylogenetic sense. The patterns we see in adults may be more a reflection of complex processes of growth and development in skeletal maturation, although processes of adaptation may be able to fine tune these patterns following function (Bromage, 1992b). Thus, while differences in elastic properties between the human mandible and supraorbit suggest a functional or biomechanical significance, the developmental and evolutionary meaning of these differences awaits further investigation.

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