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Functional Morphology of the Mandibular Symphysis of Hominoids Using the Finite Element Method

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Abstract The present study conducted structural analyses of hominoid mandibles by using the finite element method (FEM) in order to clarify functional adaptations for mastication in primate mandibular symphyses. Three-dimensional finite element models of the mandible of chimpanzee, gorilla and human were constructed, and using these models the stress distributions were compared among three species under the loading on the molar and incisor regions. Major findings are as follows. 1) Under vertical loading to the molar, high equivalent stress was observed at the lower border of the symphysis in all three species, although the magnitude of the symphyseal stresses under this kind of loading was low compared to that in the entire mandible. 2) Under horizontal loading to the molar, very high equivalent stress was observed on the lingual side of the symphysis in all three species. 3) Under loading to the incisor, very high equivalent stress was observed around the loading point and the circumference regardless of the loading orientation and the taxon because there was a load point inside the symphysis. Result 2) confirms Hylander's hypothesis that superior transverse torus (partially inferior transverse torus) was an adaptation to a horizontal external force (bite force and/or muscle force). Moreover, mentum osseum of modern human might function to resist the horizontal load on the molar, since the second peak of equivalent stresses was observed around the area corresponding to mentum osseum.

Key words Hominoid, Mandible, Mandibular symphysis, Biomechanics, Finite element method

Introduction

The fusion of the mandibular symphysis in the Anthropoidea made the mechanical characteristic of the mandible more complex. In the mammals whose symphysis don't fuse, only the axial forces (especially compressive force) are substantially transmitted between right and left mandibles (Beecher 1977), so that the mandible can be considered to act as a cantilever beam. For the mandible whose symphysis fuses, however, it is necessary to take the balancing side muscle forces and torsion into account. The anthropoid mandibular symphyses are highly differentiated, mainly because various external forces load the fused symphysis (Beecher 1977, 1979; Ravosa & Hylander 1994).

Hylander (1984) measured the in vivo bone strain at symphysis of crab-eating macaques during chewing, and speculated the external forces acting on the symphysis and the symphyseal stresses caused by those forces. The result is that there are two major sources of the symphyseal stresses. One is a lateral component of bite and/or muscle forces which causes lateral transverse bending of the mandible; this bending results in strong tension at lingual side of the symphysis. Another is the masseter muscle force that causes torsion of the mandibular corpus; this torsion results in vertical bending at the symphysis that causes compression in the upper part of symphysis and tension in the lower part of it. He concluded that the superior transverse torus might be an adaptation to the former stress, and the inferior transverse torus to the latter one. Based on his suggestion, various biomechanical studies on the symphyseal morphology were made (Ravosa 1991; Vinyard 1998; Daegling 2001). Concerning the superior/inferior transverse torus, most studies support Hylander's hypothesis.

The recent technological development of computer science has enhanced mathematical simulations such as the finite element method (FEM) (Miyoshi 1978) for bio-morphological studies. Mathematical simulation has benefits over experimental approaches. For example, simulation study enables the adoption of various parameters, thus simulating various cases more freely than in experiments on the living animal. Also, it enables the calculation of internal stress and strain distributions of the whole object.

There are numerous FEM studies of the human mandible from the medical, dentistry, engineering perspectives (Knoell 1977; Korioth *et al.* 1992; Tsutsumi *et al.* 1993). However, those on non-human primates are still scant with a few exceptions (Chen & Chen 1998). The present study conducts FEM analyses on the mandibular symphysis in hominoids in order to obtain information about general mechanical properties of this region in primates as well as to depict different functional adaptations, if any, between human and great apes.

Materials and Methods

The FEM models used in this study are based on dry bones of common chimpanzee, gorilla and human. All specimens are males and housed at the Laboratory of Physical Anthropology, Kyoto University. All of them are adult with the third molar has fully erupted but the wear is slight.

The morphological data to construct the models were obtained from three-dimensional measurements on the external surface of the bone. The spatial coordinate measuring device of the Kosaka laboratory Ltd. (VECTORON) was used for the measurements. The three-dimensional coordinate of the points corresponding to the nodes of FE models were collected, and based on these data, the three-dimensional FE models were constructed (Fig. 1). The models are composed of three-dimensional hexahedron solid (SOLID 45) elements. The number of node is 202 in chimpanzee and gorilla, and 148 in human. The number of element is 70 in chimpanzee and gorilla, and 48 in human. The materials which compose the models were assumed to be compact bone. Its Young's modulus was set to be 10000MPa and its Poisson's Ratio to be 0.20 after JSME (1988).

Assuming the bite forces acting on the mandible at power stroke phase of chewing, the loads applied to the models were set as follows (Fig. 2). The position of loading: 1) Mastication = molar biting: the node corresponding to the mesio-buccal edge of the crown of second molar (it becomes unilateral biting), 2) Incision = incisal biting: the upper bor-

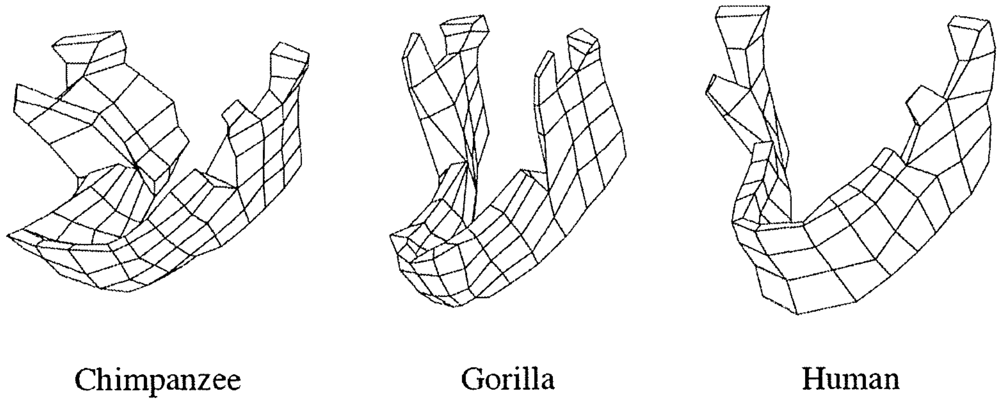

Fig. 1. Three-dimensional finite element models of common chimpanzee, gorilla and human.

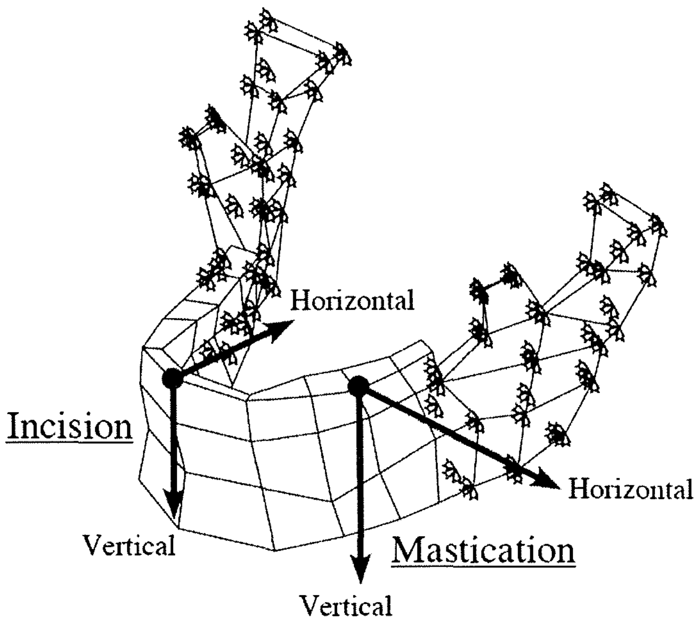

Fig. 2. The boundary conditions and the loads applied to the models. The triangle shows the node whose displacement is set to zero in all directions. The arrows show the positions and directions of four kinds of load.

der of the symphysis i.e. the mid-point between the central incisors. The direction of loading: 1) Vertical: vertically downward, 2) Horizontal: laterally directed in Mastication, and posteriorly directed in incision within the transverse plane. The magnitude of loading was set to be 500N in all the simulations. On two positions and for two directions, four kinds of load applied to the models are as follows:

Mastication Vertical,
Mastication Horizontal,
Incision Vertical,
Incision Horizontal.

For boundary conditions, the displacement of all nodes corresponding to the mandibular ramus was set to be zero in all directions. This fixation substitutes for muscle and joint reaction forces. Applying four kinds of load to three kinds of model, the equivalent stresses at the symphyseal area were compared. The units of the stress used in figures and text are all MPa. The computer program used to calculate is ANSYS Release 4.4A of the ANSYS Inc.

Results

Comparing the equivalent stress distribution among all the simulations, the difference among loads was more remarkable than that among three species. So, the results are shown by each load.

Mastication Vertical (Fig. 3)

It was common for three species that overall equivalent stresses were lower than those in Mastication Horizontal described below. In chimpanzee, the highest equivalent stress was observed at the bottom of the symphyseal cross section. Gorilla and human showed the highest stress at the lower border of the lingual side of the symphysis.

Mastication Horizontal (Fig. 4)

In chimpanzee, high equivalent stresses were observed from the mid-part to the lower border of the lingual side of the symphysis, in other words, from the superior transverse torus to the inferior transverse torus. Gorilla showed high stresses at the mid-part of the lingual side of the symphysis i.e. area corresponding to the superior transverse torus. The region of the highest stress in human was close to that of gorilla, but the level was slightly upper. And humans showed the second peak of the stress area corresponding to the mentum osseum, although the magnitude of the stress was not so large.

Incision Vertical (Fig. 5)

For three species, the results were the same. Because the load was applied in the node within the symphysis, the area around the load point showed the concentration of the equivalent stress. The stresses in the other area were much lower than those in the top of the section. The lower part of the symphysis, however, showed a little higher stress than the mid-part of the symphysis, although it is not possible to detect from the figures.

Incision Horizontal (Fig. 6)

Same as in Incision Vertical, the equivalent stresses around the load point were extremely high compared to the other part of the section among all species.

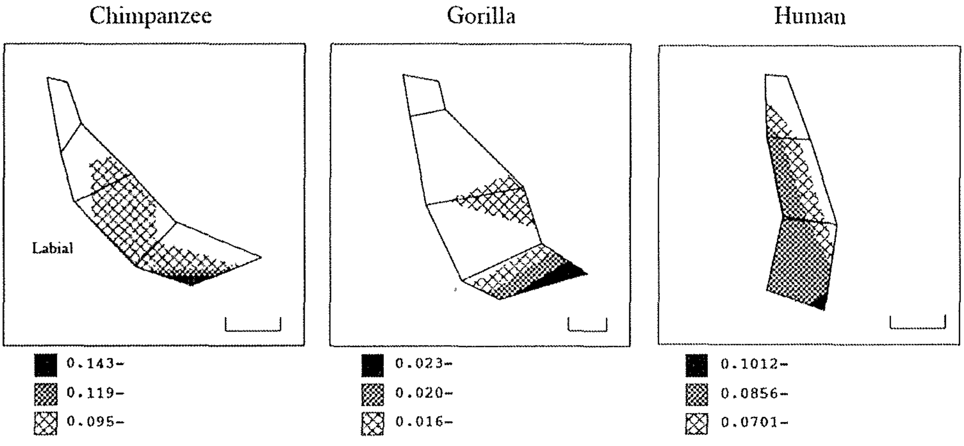

Fig. 3. The equivalent stresses in the symphyseal area under the load "Mastication Vertical". The left side of the figure is labial side. The unit of the stress is MPa.

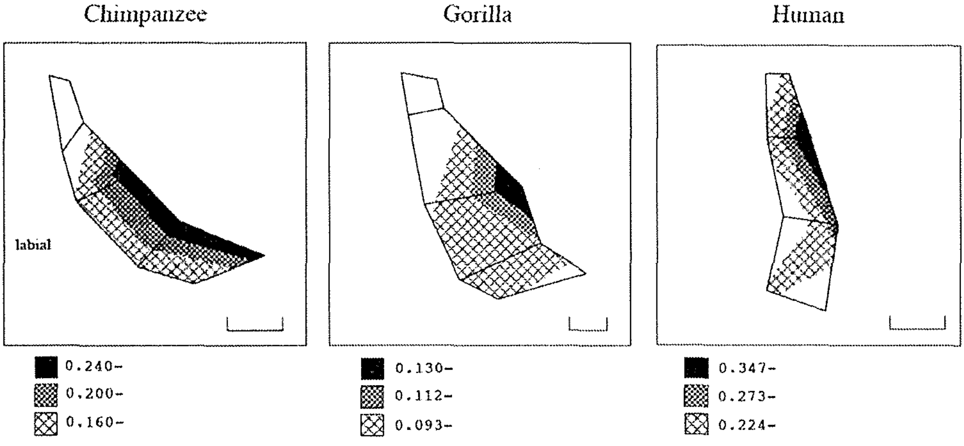

Fig. 4. The equivalent stresses in the symphyseal area under the load "Mastication Horizontal". The left side of the figure is labial side. The unit of the stress is MPa.

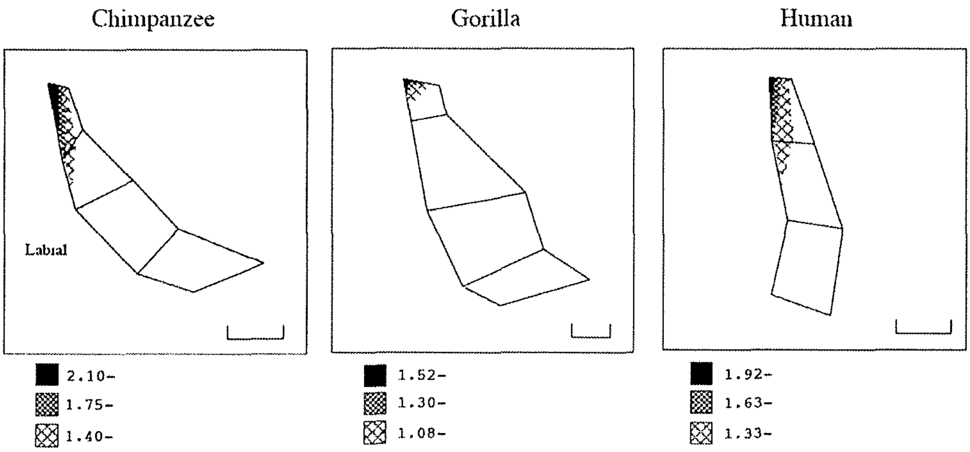

Fig. 5. The equivalent stresses in the symphyseal area under the load "Incision Vertical". The left side of the figure is labial side. The unit of the stress is MPa.

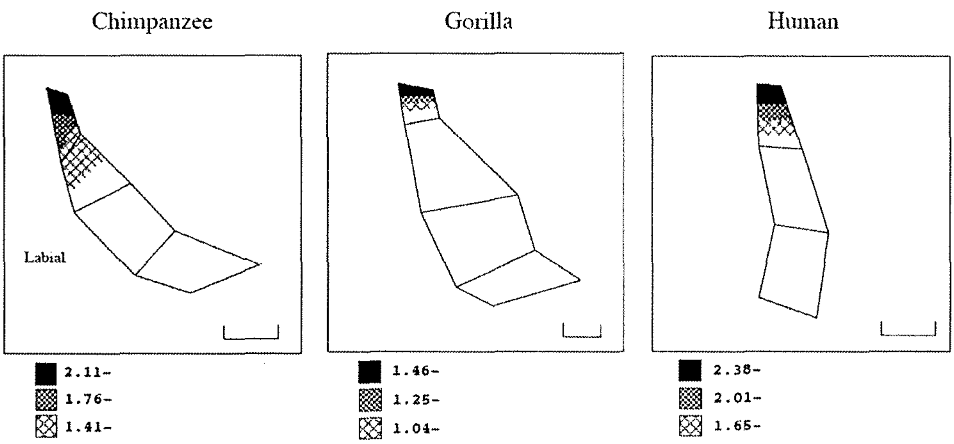

Fig. 6. The equivalent stresses in the symphyseal area under the load "Incision Horizontal". The left side of the figure is labial side. The unit of the stress is MPa.

Discussion

About Incision, it is difficult to analyze the stress distribution within the section since the stress concentration into the load point occurs. It is notable, however, that in Incision Vertical, a slightly high stress was observed in the lower part of the symphysis compared to the mid-part of the section. This suggests that the mandible is under "simple bending" by the bite force. To resist simple bending, the bone deposition at the lower part of the mandible, the inferior transverse torus, is effective (Hylander 1984).

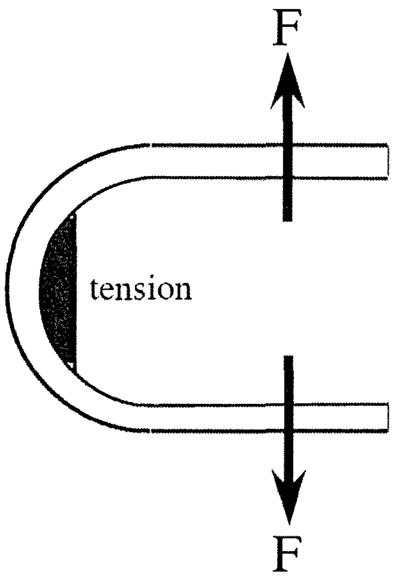

Fig. 7. The diagram of the "curved beam". F: external force in the transverse plane. When this beam model is loaded by Fs, high magnitude of tension occurs on the inner side of the arch.

In Mastication Vertical, the highest equivalent stress was observed at the bottom of the symphysis among all species. As in Incision Vertical, the stress distribution suggests that the mandible is under simple bending by the bite force. However, in Mastication the bending moment is considered to be low, because the loading point locates between the symphysis and the fixed nodes, and the loading point is far from the symphysis. Figures 3 to 6 also show that the magnitude of the equivalent stresses in Mastication Vertical are lower than that of other loading regime. To resist this bending, as in Incision Vertical, the bone deposition at the lower part of the mandible is effective (Hylander 1984).

In Mastication Horizontal, the peak of the equivalent stresses was observed at the lingual side of the symphysis in all species. Among the principal stress in this region, tension was dominant. According to Hylander (1984), the lateral component of the external force causes the lateral transverse bending ("wishboning") of the mandible and this bending results in the strong tension at the lingual side of the symphysis. This is the so-called "curved beam" in terms of the strength of materials (Fig. 7). Hylander (1984) proposed that developing the superior transverse torus (partially inferior transverse torus) might be to resist this tension at the lingual side. The "curved beam" scheme matches the result of Mastication Horizontal. Thus, the stress distribution of Mastication Horizontal supports Hylander's hypothesis. Although in all species high equivalent stresses were observed at the lingual side, the locations of the peak stress were different from each other (Fig. 5). The cause of this difference might be from the fact that if there were the protruding part at the lingual side, the bending stresses would be resisted on that part. In the model of gorilla used in the present study, the superior transverse torus is well-developed compared to that of chimpanzee. So, the symphysis of gorilla showed high stress at mid-part of the lingual side. Since the model of chimpanzee has less-developed superior transverse torus and well-developed inferior transverse torus i.e. simian shelf, the high stress may occur from the mid-part to the lower border of the lingual side of the symphysis.

In human Mastication Horizontal, the second peak of the equivalent stresses were observed at the lower border of the labial side of the symphysis i.e. mentum osseum, although the magnitude of the stresses were relatively small. This suggests that there is a possibility that developing mentum osseum is effective to resist to the lateral bite force. In Daegling's (1993) review on biomechanics of mentum osseum, he hypothesized that it might be an adaptation to tension at the lower border of the symphysis due to torsion of the mandibular corpus generated by masseter muscle forces. However, the external forces that cause the stress at the mentum osseum of the present study different from Daegling's hypothesis. From the symphyseal morphology of middle to late Pleistocene fossil hominids, Dobson and Trinkaus (2002) concluded that mechanical adaptation is not sufficient to interpret the emergence of human "chin". To test which hypothesis is reasonable, further research on both of morphology and biomechanics of the symphysis, is required.

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References

Beecher, R. M. 1977 Function and fusion at the mandibular symphysis. Am. J. Phys. Anthropol. 47: 325-336.

Beecher, R. M. 1979 Functional significance of the mandibular symphysis. J. Morphol. 159: 117-130.

Chen, X. & H. Chen 1998 The influence of alveolar structures on the torsional strain field in a gorilla corporeal cross-section. J. Hum. Evol. 35: 611-633.

Daegling, D. J. 1993 Functional morphology of the human chin. Evol. Anthropol. 1: 170-177.

Daegling, D. J. 2001 Biomechanical scaling of the hominoid mandibular symphysis. J. Morphol. 250: 12-23.

Dobson, S. D. & E. Trinkaus 2002 Cross-sectional geometry and morphology of the mandibular symphysis in Middle and Late Pleistocene *Homo*. J. Hum. Evol. 43: 67-87.

Hylander, W. L. 1984 Stress and strain in the mandibular symphysis of primates: A test of competing hypotheses. Am. J. Phys. Anthropol. 64: 1-46.

JSME (ed.) 1988 Mechanical engineers' handbook, engineering, C6: Biotechnology and medical engineering. Maruzen, Tokyo (In Japanese).

Knoell, A. C. 1977 A mathematical model of an in vitro human mandible. J. Biomech. 10: 159-166.

Korioth, T. W. P., D. P. Romilly & A. G. Hannam 1992 Three-dimensional finite element stress analysis of the dentate human mandible. Am. J. Phys. Anthropol. 88: 69-96.

Miyoshi, T. 1978 An introduction to finite element method. Baifukan, Tokyo (in Japanese).

Ravosa, M. J. 1991 Structural allometry of the prosimian mandibular corpus and symphysis. J. Hum. Evol. 20: 3-20.

Ravosa, M. J. & W. L. Hylander 1994 Function and fusion of the mandibular symphysis in primates: Stiffness or strength? In: J. G. Fleagle & R. F. Kay (eds.) Anthropoid origins. pp. 447-468. Plenum Press, New York.

Tsutsumi, S., Y. Maeda & M. Sogo 1993 Biomechanical influences of the cranio-maxillo-facial system on its form and function. Theor. Appl. Mech. 42: 299-305.

Vinyard, C. J. & M. J. Ravosa 1998 Ontogeny, function, and scaling of the mandibular symphysis in papionin primates. J. Morphol. 235: 157-175.