Biomechanical Simulation Study on the Forms of the Frontal Bone and Facial Bones of the Recent Human Facial Skeleton by Using a Two-Dimensional Frame Model with Stepwise Variable Cross-Section Members

By

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Summary: The form in frontal view of the recent human facial skeleton, including the frontal bone, was simulated under the condition of uniform strength to cope with the forces in the chewing action, by using the two-dimensional frame model made of members with step-wise variable cross-sections and by using the finite element analysis method. The simulation, in which the condition was applied to the elements of the model in the frontal bone region, resulted in a form different from the actual facial skeleton. But the simulation in which the condition was not applied to the above elements resulted in a form tolerably similar to the actual facial skeleton. Hence, it was concluded that the biomechanical role of the frontal bone was different from that of the facial bones: the former was part of the brain casing and the latter a chewing machine, including the casings of the eyes and the nose, regulated by the law of uniform strength to cope with the forces in the chewing action.

Previously, Endo, one of the authors, published a series of papers dealing with the biomechanical analysis of the human facial skeleton using various methods (Endo, 1965, 1966a, 1966b, 1970a, 1970b; Endo and Fukushima, 1973). The results of these papers concerned with experimental analyses of stress and strain in the facial skeleton have been used by a number of researchers studying skull morphology or biomechanics for their discussions, such as Alexander (1968), Tappen (1973), Zingeser (1974), Carlson and van Greven (1977), Cachel (1979), Oyen, Rice and Cannon (1979), Oyen, Walker and Rice (1979), Russell (1982), Smith and Ranyard (1982), Campbell (1983), and Olsen (1985). Only Hylander (1977) criticized them as inaccurate, mainly because these analyses were not based on in vivo measurements, which are, however, impossible in the case of the human facial skeleton.

Among Endo's papers listed above, there were simulation studies of the human facial skeleton using various two-dimensional frame structure models (Endo, 1966a,
1970a). But the results obtained from these models of the facial skeleton showed its biomechanical significance only qualitatively. The quantitative relationship between the facial skeleton form and the stress or internal force (cross-sectional force) has remained unsolved. Thereafter, no one has followed and developed such a simulation study in terms of biomechanics, but the results already obtained from these models were used for the interpretation of the form or structure of the facial skeleton by some morphologists, such as Vilmann and Moss (1980), Wolpoff (1980), Rak (1983) and Russell (1985).

Only Wolpoff and Rak tried to design frame structure models of the facial skeleton for *Homo erectus* and *Australopithecus* respectively, by deforming Endo’s model. But they did not analyse their models in terms of mechanics, and such unsolved models cannot be biomechanical models representing the facial skeleton of the fossil hominid.

In the papers dealing with the frame structure model, Endo suggested that the structure of the human facial skeleton is likely to be the structure regulated by a law close to the law of uniform strength to cope with the forces produced by the chewing action as a chewing machine, having the casings of the eye and the organs in the nasal cavity and aperture as the prerequisite. The law of uniform strength mentioned above is an approximation of Roux’s hypothetical law, i.e., the law of maximum strength with minimum amount of material (Roux, 1895).

The background for the existence of such a law is the homeostatic equilibrium of the strength of bone tissue, which is almost certainly regulated by the osteocyte, osteoblast and osteoclast, sensing the piezoelectric charge of bone matrix due to its stress as the main signal for the regulation, and this means that a homeostatic feedback system exists for supporting the equilibrium (Bassett, 1971). The above fact is now beyond doubt, though there still remain unsolved problems. The piezoelectric charge intensity is known to be parallel to the stress intensity produced by the external force acting on the bone. If this electric charge is high or the electric field produced by this charge is strong in an arbitrary part of the bone, this part is reinforced by the apposition of bone tissue, and if the charge is low or the field is weak, this part is weakened by the absorption, according to Bassett (loc. cit.).

In the case of the skull, however, careful attention should be paid. The craniofacial bones are functionally and ontogenetically separated. First, the bones of the neurocranium are parts of the protective casings of the brain and other organs with a neural origin, while the other bones form the jaw skeleton, which acts as a mechanical machine; second, the calvaria consists of membranous bones developed from the *ectomeninx* which originates from the mesoderm (Hamilton and Mossman, 1972), while the facial bones, both cartilagenous and membranous, developed from the neural crest mesenchyme (Noden, 1978, 1983). Only the lower part of the frontal bone, at least, seems to be formed by both the mesoderm and the neural crest mesenchyme (Noden, loc. cit.).

The problem in this study is to investigate quantitatively, by the model-simulation method, whether the strength of the whole facial skeleton, consisting of the facial bones and the lower part of the frontal bone to cope with the forces produced by the chewing action, is uniformly so controlled as to produce a certain stress intensity as that of the structure of uniform strength, or whether the frontal bone is regulated differently.

The model used for solving the above problem in this study was the two-dimensional frame structure model, which
consists of members of step-wise variable width, representing the frontal view of the human facial skeleton.

The reasons why the frame structure model was selected in this study were that the results could maintain continuity with the results of the former model analysis by Endo (loc. cit.), and that the understanding of the internal forces and stresses distributed over the model was the easiest of the various kinds of structures.

Model-simulation study has a marked advantage for investigating undestroyable specimens or hurt-prohibited living humans because it does not damage or hurt the object at all, even though it is always a kind of approximative study.

Materials and Methods

Materials were three macerated skulls of adult male. Recent Japanese preserved in the Medical Department of the University Museum, The University of Tokyo.

The model for this biomechanical simulation study is a two-dimensional frame structure, representing the frontal view of the skull set on the alveolar horizontal plane.

For the purpose of designing the model, the skull was set as described above with a scale on an adjustable stand having six degrees of freedom of movement. A photograph was taken by a 35mm-film camera through a lens having 1000mm focal length, i.e., an ultralong focus lens. Thus, the approximate orthographic projection of the facial skeleton could be photographed. Then the photograph was enlarged to exactly the natural size by measuring and adjusting the scale length on the sheet of plastic-covered shrinkless print paper.

The contour of the facial skeleton of natural size was traced onto the plastic tracing sheet covering the photograph obtained, as described above (Fig. 1A).

The two-dimensional model, which consisted of straight beams (members), was designed on the contour figure by estimating the longitudinal axes of various parts of the facial skeleton with the aid of observation of the photograph and the original skull. The model thus designed had, as a matter of course, the spaces of the orbitae and of the nasal piriform aperture enclosed by the members. This means that the model had the mechanical role not only of resisting the biting force by forming the chewing machine, but also of protecting the eye and the nasal organs by forming the casings for them as its prerequisite, in the same way as the actual facial skeleton.

The number of members of the model thus designed was 17; only the lowest long horizontal beam, which corresponded to the alveolar region, was divided into two beams at the median point to separate right and left. Then, each member was divided into three elements, as shown in Fig. 1B. The initial width of each element was determined from the measurement of the width of the corresponding part of the contour figure and from an estimation of the effective width considering the shape of the corresponding part of the photograph and of the original skull.

The model was acted on by forces corresponding to the chewing force on the tooth and the forces caused by the contraction of the principal chewing muscles, i.e., the temporalis and the masseter muscles, at the points (nodes) corresponding to their origins, as seen in Fig. 1C. The force acting on the mandibular joint is neglected because its intensity is far lower, compared with the above forces owing to the moment caused by the above two muscles, according to Crompton (1963).

The relative intensities of the forces of the temporalis and the masseter muscles were approximated as equal. It is because the area of the physiological cross-section, which is considered to be parallel to the
Fig. 1. Procedure of designing the two-dimensional frame model for simulating the form of the human facial skeleton in frontal view. A, form of the right half of the facial skeleton traced from the photograph; B, designed frame model divided into elements for the computation of the finite element analysis method, with its external forces, where dots indicate nodes of elements; C, geometrical positions of the applied external forces; D, equations of the external forces in equilibrium, where $F_{d_{jk}}$ is constant in case from $k=1$ to 7 as shown in C.
maximum contraction force intensity of the muscle, is, though to some degree larger in the temporalis muscle than in the masseter muscle (Schumacher, 1961), the area effective in producing the biting force in the former is to some degree smaller than its whole area. The reason of this point is that the posterior belly of the temporalis muscle is so inclined as to be nearly horizontal. These muscles attach to the mandibular ramus at almost the same horizontal position, located at around the midpoint between their origins. Therefore, the resultant of these two muscle forces was positioned to pass through the midpoint between their origins.

The force in the model corresponding to the chewing force ($F_{di}k$) successively moves from node to node (from $k=1$ to $k=7$) at a constant intensity, as shown in Fig. 1C. All the above external forces acting on the model were vertically directed in order to simplify the problem, because it is likely that the principal direction of these forces in the actual face is vertical. Being simplified as above, the equilibrium of the above forces in the model could be determined as shown in Fig. 1D.

Because the equilibrium of the bone form with a homeostatic feedback system as maintained by Bassett (loc. cit.) can be expressed as the bottom figure of Fig. 2 (the same kind of figures have already been drawn by Becker, Bassett and Bachman, 1964, as well as by Kummer, 1972), the equilibrium of the model form with a similar feedback was defined as shown at the top of Fig. 2. In the case of bone, the target to be variable is bone thickness, while in the case of the model it is the element width, because the model is two-dimensional.

Hence, the width of most of the elements of the model were variable during the computation according to the intensity of the maximum stress obtained from each computation routine. But the initial widths of the elements positioned in the region corresponding to the alveolar region were not variable but constant throughout the computation, because the widths of the alveolar region seem to be determined by the length of teeth roots and their necessary tissues. Instead, their thicknesses were variable.

In this study, the estimated width of the elements positioned in the region corresponding to the frontal bone region was set as to both variable and invariable in order to detect the difference of the mechanical role of the frontal bone when compared with that of the facial bones.

According to the closed feedback circuit shown on the top figure of Fig. 2, a computation program for microcomputer was designed for simulating the form of the frontal view of the recent human facial skeleton under the condition of the law of uniform strength of structure to cope with the forces produced by the chewing action and the additional condition that the area of the structure in frontal view was unchanged from its initial area. In other words, the structure form obtained as the result of simulating the facial skeleton form was the structure of uniform strength for all kinds of applications of force corresponding to the chewing force acting on teeth, having approximately the same size as the original facial skeleton. The program was written in BASIC, referring in part to the manual written by Togawa (1982). Its flowchart is shown in Fig. 3.

The standard maximum stress intensity of each element, as the criterion of uniform strength, was set to be 7 [N/mm²], which was approximately 1/20 of the ultimate strength of the usual bone, and the longitudinal elasticity modulus to be 18000 [N/mm²] (cf. Yamada and Evans, 1970). The allowances of the maximum stress intensity and the area were both ± 2.5% of the standard stress and the initial area.
Fig. 2. Comparison between the feedback systems of the element of the model (top) and the actual bone part (bottom).
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Fig. 3. Flowchart of the computation for simulating the form of the facial skeleton by using the frame model, under the condition of uniform strength to cope with the forces produced by the chewing action.

Geometrical properties:
- Number of nodes ($n$) designated as $p=1,2,\ldots,n$
- Number of elements ($m$) designated as $i=1,2,\ldots,m$
- Number of nodes ($a$) successively acted on by the force ($Fd_{ik}$) designated as $k=1,2,\ldots,a$
- Positions of nodes ($x_p, y_p$) where $p=1,2,\ldots,n$
- Thicknesses of elements ($T_{ii}$) where $i=1,2,\ldots,m$, which are constant except the ones specified to be variable
- Initial widths of elements ($W_{ii}$) where $i=1,2,\ldots,m$, which are variable according to $j$ as $W_{ij}$ except at start fixed ones

Mechanical properties (for all elements):
- Elasticity modulus ($E$) & Standard stress ($\sigma_s$)
- Initial forces ($j=1$):
  - Force corresponding chewing force of tooth ($Fd_{ik}$) which is constant between $k=1$ & $a$, but variable according to $j$
  - Forces corresponding to muscle forces of the Temporalis & the Masseter of right and left ($Frt_{ik}, Flt_{ik}, Frm_{ik}, Flm_{ik}$)

FINITE ELEMENT COMPUTATION

1. $j = j + 1$, where $Fd_{i+1k} = \alpha Fd_{ik}, W_{ij}, T_{ij}, A_{ij}$
2. $AF_{j+1} = AF_j$

Computations of correction on each element to obtain:
- $W_{ij}$ except for width-fixed elements $T_{ij}$ of the specified elements
- Aiming $|\sigma_{ij}|_{\text{max}} = \sigma_s$
- $AF_{j} = AF_{\text{init}}$
  - where $j'$ is the corrected case of $j$

Selection of absolute maximum stresses ($|\sigma_{ij}|_{\text{max}}$) among absolute maximum stresses ($|\sigma_{ij}|_{\text{max}}$) in all the cases of $k$ where $\alpha \in k (k=1,2,\ldots,a)$

$|\sigma_{ij}|_{\text{max}} - \sigma_s \leq 0.025$ and $|AF_j - AF_{\text{init}}| \leq 0.025$

RESULTS OUTPUT

End
respectively.

The principal part of the computation was the finite element analysis, as has been well explained in many text-books, such as Zienkiewicz and Cheung (1967). However, as stated before, the model structure is the frame. Therefore, the computation method is slightly different from that of the ordinary finite element analysis. The difference was based on the condition that the node of the ordinary element was acted on by the two forces which were orthogonal to each other, while the node of the beam element in the present case was acted on by the bending moment, in addition to the above two forces, as seen in Fig. 4.

Details of the geometrical and mechanical characters of the model are shown in Table 1.

![Diagram](image)

**Fig. 4.** Comparison between the sets of the nodal forces of the ordinary element and of the beam element used in the finite element analysis.

A large scale microcomputer (Sord M68) with a CPU of M68000 (4 MByte) was used for this computation. The program was

<table>
<thead>
<tr>
<th>Table 1. Characters of the frame model of the facial skeleton of natural size.</th>
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<tbody>
<tr>
<td>Number of members</td>
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<tr>
<td>Number of elements</td>
</tr>
<tr>
<td>Number of nodes</td>
</tr>
<tr>
<td>Number of nodes acted on by the force corresponding to the muscle force of the r &amp; 1 Temporalis &amp; Masseter</td>
</tr>
<tr>
<td>Number of nodes successively acted on by the force corresponding to the chewing force on tooth</td>
</tr>
<tr>
<td>Thickness of element constant throughout computation</td>
</tr>
<tr>
<td>Thickness of element specified to be variable</td>
</tr>
<tr>
<td>Initial width of element varied during computation</td>
</tr>
<tr>
<td>Width of element constant throughout computation in the alveolar region</td>
</tr>
<tr>
<td>Effective width of element of the forehead region being either constant or variable</td>
</tr>
<tr>
<td>Modulus of longitudinal elasticity</td>
</tr>
<tr>
<td>Intensity of the standard stress (1/20 of ultimate strength)</td>
</tr>
<tr>
<td>Initial force corresponding to the chewing force on tooth</td>
</tr>
<tr>
<td>Ratio between the forces corresponding to the muscle forces of the Temporalis &amp; the Masseter on the same side</td>
</tr>
<tr>
<td>Intensity of the forces corresponding to the muscle forces</td>
</tr>
</tbody>
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**Fig. 5.** Forms of the initial model and final model simulated to the form of the facial skeleton. In each figure, the right half is the form of the actual facial skeleton and the left half the form of the model. A, model form consists of initially input element widths; B and C, two kinds of simulated model form obtained as the results, where C is the successfully simulated form. For further explanations, see text.
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(A) Actual facial skeletal area

(B) Width-variable area

(C) Invariable area

Legend:
- Actual facial skeletal area
- Width-variable area
- Thickness-variable area
- Invariable area

0 5cm
divided into two parts: the data input to the
disk as the preparatory program, and the
computation beginning from the data
reading from the disk as the main program.
The latter is shown in the form of the
flowchart in Fig. 3.

Results

The computation for simulation was
carried out for each specimen, but the
characteristics of the results were mainly the
same. Therefore, the results of the simul-
ation will be described for a representative
specimen.

As described before, two kinds of
computation for simulation were executed.
In the first case, the width of the elements in
the region corresponding to the frontal bone
region was set to be variable, and in the
second case, it was consistently invariable
from the width input initially. The results of
the computation of these two cases were
quite different from each other, as can be
seen in Fig. 5.

Figure A in Fig. 5 is the form of the
model with the initial element widths
measured on the photograph of the skull or
estimated from the intact skull. Figure B is
the form of the model obtained as the result
of the computation for simulation of the
first case, while Figure C is the form of the
model obtained as the result of the
computation of the second case.

In the first case, the form of the
simulated model of uniform strength, shown
as Figure B, markedly differed from the
form of the model before the computation
for a simulation (Figure A). This fact means,
as a matter of course, that it is clearly
different from the form of the facial
skeleton. In this case, the prerequisite was
lost as described below and subsequently the
simulation of this case was unsuccessful.

The elements in the region of the frontal
bone, including its nasal process region,
disappeared. In other words, the width of
these element became zero. On the other
hand, all the elements in the zygomatic,
infraorbital and maxillary regions became
very wide, showing that these regions were
all robust. It was because the material of the
elements in the frontal bone region was used
for strengthening the elements in the
maxillary and zygomatic regions, causing the
elements in these regions to widen.

Consequently, the force \( F_{djk} \) of the last \( j \), cf.
Fig. 1C and Fig. 3) corresponding to the
biting force reached an intensity of 373.1
\[ N \]. Because of the remarkable widening
of the elements in the medial maxillary
region, the nasal aperture was extremely
narrowed. Thus, it is quite different in form
from the actual nasal aperture of the facial
skeleton. These features can be easily
explained on the basis of the influence-lines
diagrams of the internal forces (cross-
sectional forces) shown in Fig. 6A.

These diagrams show the influence lines
of the internal force produced in the left
half of the model, because the model is
symmetrical. The diagrams were also
obtained from the results of the computa-
tion for simulation to obtain the form of a
structure of uniform strength. The diagrams
show very strong internal forces in the
remaining elements. An extremely strong
bending moment appeared in the medial part
of the infraorbital region. It should be noted
that the bending moment among the internal
forces has far stronger influence on the
strength of beam or frame than the other
internal forces, and that the width of the
beam element is the most important
geometrical factor for its strength to cope
with the bending moment. Thus, the
elements in the above-mentioned part
became very wide, as seen in Fig. 5B. This is
the reason for the extreme narrowing of the
nasal aperture.

Contrary to the above results obtained
from the first case of computation for
Fig. 6. Diagrams of the influence lines of the internal forces (cross-sectional forces) of the left half of the model. In the diagrams of the axial forces + is tensile and – is compressive. A is the diagrams of Model B, and B of Model C in Fig. 5.
simulation, the simulated uniform strength form of the model in the second case of computation, shown as Figure C, was very similar to the form of Figure A.

Consequently, it was tolerably similar to the actual form of the facial skeleton, also having openings similar to the orbita and the nasal aperture. In this case, the force corresponding to the biting force was 254.2 [N].

The diagrams of the influence lines of internal forces in this case show less intense internal forces than the first case, as shown in Fig. 6B. A relatively high magnitude of the bending moment can be seen both in the medial marginal part of the frontal bone region and the infraorbital region. But these magnitudes are far lower than the magnitude of the infraorbital region in the first case of computation. The appearance of the high magnitude in the medial part of the frontal bone region means that the medial supraorbital and the grabellar region is acted on quite a strong bending moment when the normal frontal bone exists.

The results of the above two cases of computation for obtaining the form of uniform strength indicate that the mechanical role of the frontal bone is quite different from that of the facial bones, and that the form of the facial bones, being reinforced by the frontal bone, is well adjusted to form a structure of uniform strength to cope with the forces in the chewing action, protecting the eyes and nose positioned in the structure by forming their casings, because the frame structure in this case primarily plays the role of casing and secondarily the role of chewing machine.

It is also evident that the structure of the facial skeleton consists of the facial bones and also of the frontal bone, at least its lower part, and it is well adapted to cope with the forces in the chewing action though the principal role of the latter is different.

**Discussions and Conclusions**

The results of a series of studies on the fetal development of the human anencephalic skull, carried out by Fields, Metzner, Garol and Kokich (1978), Garol, Fields, Metzner and Kokich (1978), and Metzner, Garol, Fields and Kokich (1978), show that the frontal bone develops only in the suprazygomatic, supraorbital and grabellar region, and that the bones and bone parts for forming the roof and walls of the neurocranium are completely absent, but that the facial bones are developed to form the facial skeleton, though it is considerably deformed. The remaining frontal bone seems to play the role of the casing of the eye and to form part of the facial skeleton.

This part of the frontal bone seems to be formed mainly by the neural crest mesenchyme, as is the case with most of facial bones, considering the results of the embryological studies carried out by Noden (1978, 1983, 1984), and this seems to be the reason for the development of such a frontal bone.

The results of this study suggest that there is no need to form the frontal bone as a pure chewing apparatus or machine but that the orbital roof and walls formed by the frontal bone are a necessary prerequisite for the formation of the facial skeleton.

Thus, all the facts, estimations and inferences described above coincide with each other. The part of the frontal bone mentioned above behaves as part of the facial skeleton. Consequently, the frontal bone is stressed by the forces produced by the chewing action, as the results of this study show (cf. Fig. 6B). Therefore, the frontal bone, at least its lower part, is a part of the chewing machine. The same point has already been suggested by Weidenreich (1941).

The strains in the frontal bone caused by the stresses due to the forces in the biting
action are considerably less intense than those in the facial bones in the case of recent humans, as reported by Endo, one of the authors, (1965, 1966a) based on the results of strain measurement in his experimental studies. This difference suggests that the law of uniform strength to cope with the forces produced by the chewing action cannot be applied to the frontal bone. This fact is clarified in this study, because the simulation of the form of the facial skeleton as a chewing machine under the condition of uniform strength to cope with the forces in the chewing action could succeed only in the case that this condition did not apply to the frontal bone region.

For a chewing apparatus or machine, deformation, which may be regarded as the results of the integration of strains caused by stresses due to the biting action, is not important, but strength is important. However, for the casing of the brain, deformation is important: the relatively large deformation is dangerous, because it damages the soft and fragile brain though this is protected by various membranes, some soft and some relatively hard. Therefore, it is necessary that the brain casing, including the frontal bone, should be thick and strong, so as to avoid deformation caused by various external forces. This seems to be the reason for the very thick bone formation of the neurocranium as compared with the formation of the facial bones, which are rather thin. Hence, it can be concluded that the mechanical role of the frontal bone and that of the facial bones are clearly different.

Apparently corresponding to the above conclusion, the development in size and the thickening of the bones of the brain casing, according to the experimental studies carried out by Mütke and Meyer-Glauer (1977) and Mossaz and Kokich (1981). Moreover, it becomes tolerably clear that the mechanical stress in the dura, caused by various mechanical factors including blood pressure, stimulates the osteogenesis of the brain case, according to Mütke and Meyer-Glauer (loc. cit.) and Oudhof and van Doorenmaalen (1983).

Therefore, it seems tolerably certain that the formation of bones of the brain casing is also controlled by the mechanical stress or piezoelectric charge produced by this stress like that of the facial bones, which this study has clarified fairly well, but that the source of stress, the stress intensity and the mechanism for stimulating the osteogenesis are different between the two kinds of bone described above. Thus, it can be concluded that the biomechanical roles of the frontal bone and of the facial bones are quite different.

Nevertheless, the supraorbital surface structures seem to be influenced by the stresses due to the forces produced by the chewing action. But this point cannot be clarified by the method used in this study. It will be analysed by the authors in the near future.

It should be noted that this study still depends on a relatively approximative method, because the beam which is too short does not exactly follow the beam theory for stress analysis. But our method will be further developed in future by the authors, and the results and conclusions of this study will be verified by new simulation methods.

This model simulation method was also applied to the facial skeletons of fossil hominids. The results of the above study will be published elsewhere in the near future.
References


