Distribution of Stress and Strain Produced in the Human Facial Skeleton by the Masticatory Force

Banri Endo

On account of its functional and phylogenetic importances, the mechanical significance of the human facial skeleton has interested many anthropologists, anatomists, and odontologists. Most of the works on the subject were assumptions or inferences made from the radiographs and the split-lines. Görke (1926) studied X-ray photographs and conceived the stress trajectories in the facial skeleton due to chewing action. Also on the basis of radiographs of the skull, Richter (1920) surmized a principal frame structure of the facial skeleton resisting the chewing force. Benninghoff (1925) demonstrated the spilt-line patterns in the human facial skeleton and asserted that the lines show the stress trajectories caused by the masticatory force. Bluntschli (1926) and Sicher and Tandler (1928) respectively assumed the patterns of so-called "Pfeiler" (pillars) resisting biting force, along which most of stresses were supposed to pass through. The split-lines in the facial skeleton were also studied more extensively by Tappen (1953, 1954).

However, few facts have been brought out pertainning to the actual condition of stresses in the facial skeleton produced by chewing force. Even the existence of the relationship between the split-lines and the stress trajectories was doubted and disputed by some authors. Under these circumstances the author of the present paper attempted to clarify the above-mentioned matter and already reported preliminarily some facts on the subject obtained from experimental studies (1960, 1961).

The present paper is part of a larger study on the biomechanical significance of the human facial skeleton by means of experimental analysis of stress and strain in the facial skeleton due to the masticatory force. The present paper deals with the distribution of stress and strain in the human facial skeleton excluding the mandible. Further facts and discussions on the biomechanics of the facial skeleton such as the relation of its form or architecture to mechanical function, the role of the mechanical factor to the formation of the facial skeleton, or the relationship between the form and the strength of the skull, will be described in another paper (Endo, in press).

MATERIALS AND METHODS

The materials used in the present paper consisted of 21 skulls which were

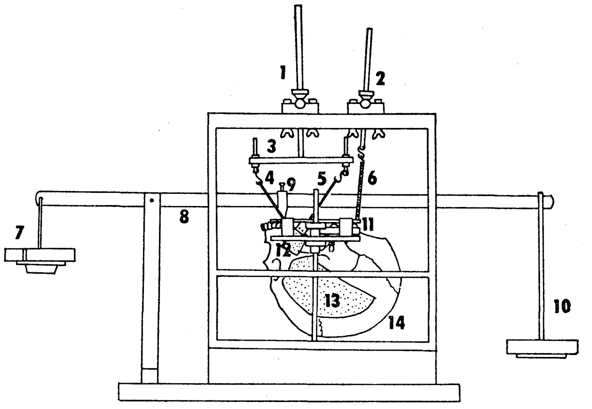


Fig. 1. The loading apparatus for the skull to reproduce mechanical condition of the occlusion.
1. suspender of the balancing bar with rotatable support, 2. suspender of the limp coil-spring with rotatable supprt, 3. balancing bar, 4. suspending rod for a canvas sheet attached to the arising area of the temporalis muscle, 5. suspending rod for a canvas sheet attached to the arising area of the masseter, 6. limp coil-spring connecting the foramen magnum with the suspender (2), 7. balancing weight, 8. lever for loading, 9. loading piece of the lever for application of the load on a tooth, 10. weight for loading, 11. rail for the roller support attached to the mandibular fossa, 12. canvas sheet attached to the arising area of the masseter, 13. canvas sheet attached to the arising area of the temporalis, 14. skull suspended in the frame of the apparatus.

unearthed from modern tombs in Joshin Temple, Fukagawa, Tokyo and were kept by the Department of Anthropology, Tokyo University. The quality of the skulls was as complete and as elastic as that of macerated skulls.

For measuring strains, electric wire strain gauges (Shinkoh S_{121} single axial of 4×1.5 mm and Shinkoh RL_{21} three axial of 8×2 mm) and a indicator (Shinkoh LT) were used. Three S_{121} were also combined to make a three axial gauge in certain cases. The gauges were attached over all part of the facial skeleton by nitrocellulose cement. The sutures of the skull were fixed by adhesive cement of epoxite.

A special apparatus was built to apply those forces to the skull which are presumably similar to those produced in the act of mastication in a living body. The apparatus was devised to produce four kinds of forces corresponding to the following forces in mastication: the tension of the temporalis muscle, the tension of the masseter, the force acting on the mandibular fossa, and the force acting on an arbitrary tooth. Those forces were applied to each skull in a condition approximately identical to that of natural masticatory act. The structure of the apparatus is illustrated in Fig. 1 and the forces acting on the skull set in the apparatus is shown schematically in Fig. 2 along with a realistic figure of the skull with muscles. The problem on the similarity of the action of apparatus to that of natural mastication will be discussed in detail elswhere (ENDO, in press).

In the experiment a skull was set in the apparatus as seen in Fig. 1 and a constant load of 4.5 kg was applied to an arbitrary tooth of the skull vertically to its occlusal plane, while the other force were produced as the reactions of the apparatus. The strains occurring in various part of a facial skeleton due to

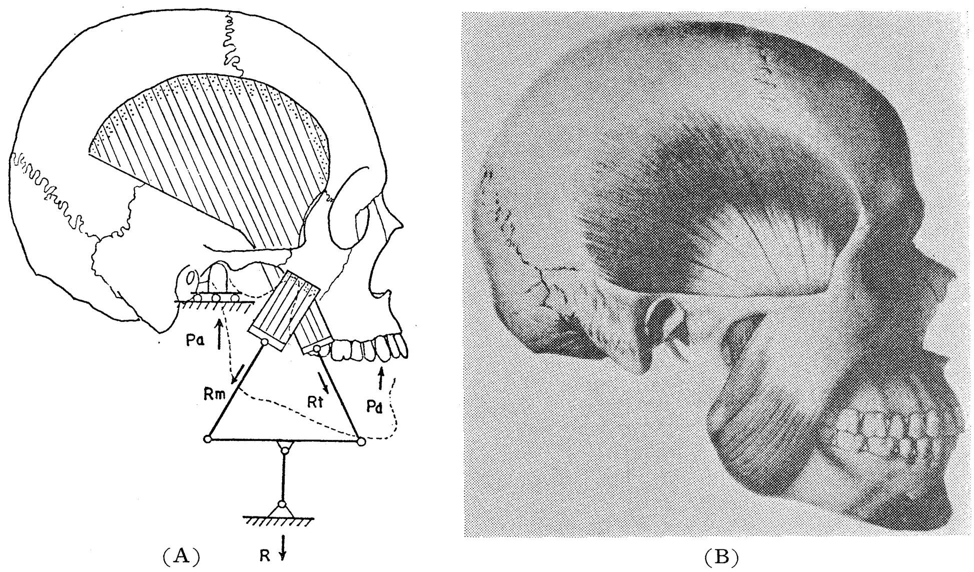


Fig. 2. A diagram to indicate the artificial forces acting on the skull (A) and profile of the skull with the temporalis and masseter (B).
Pa: vertical force on the mandibular fossa, Rm: tension of the canvas sheet corresponding to the masseter, Rt: tension of the canvas sheet corresponding to the temporalis, Pd: vertical force on an arbitrary tooth corresponding to a biting force. $\vec{R}_m+\vec{R}_t=\vec{R}$, $R_m=R_t$. The hatched parts show the canvas sheets and the dotted areas in them are glued to the skull. The figure (B) from SICHER and TANDLER (1928).

the loading were measured with an accuracy of 1×10^{-6}. The loading was made on each of all the teeth of a specimen.

Although the stress and strain in the bone obey the low of proportion to considerable extent as reported by many authors, the strains were treated as they were without being converted into stresses in the present paper, because the bone is anisotropic and its mechanical properties are different among individuals, kinds, or regions of the bone as reported by EVANS and LEBOW (1951), YOKOO (1952), and KO (1953). However, there are many identical or similar points between the behaviors of the stress and of the strain in the bone. Accordingly, the behavior of the stress in the facial skeleton can be considerably deduced from that of the strain.

RESULTS

The strain measured in different specimens under the same condition varied from specimen to specimem to some extent, but showed fairly uniform tendencies. The magnitude of strains in the facial skeleton was found to change as the load was shifted along the dental arch. A strain measured at an arbitrary point in the facial skeleton tended in most cases to increase as the load moved forward,

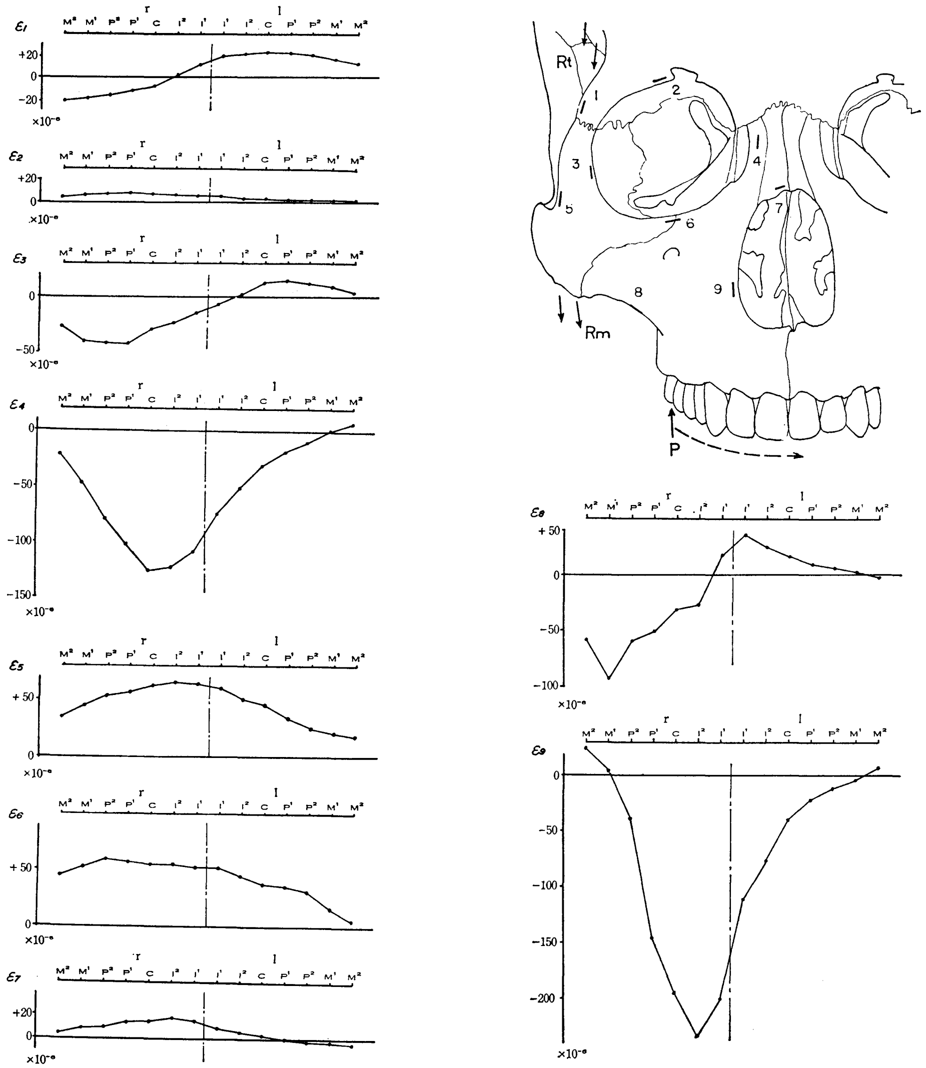


Fig. 3. Influence lines of strains in a facial skeleton due to the shift of the load P along the dental arch.
In the above right figure short bars indicate the measuring points and directions of the single axial strain gauges. The strains measured at those points are denoted by numbers of the above figure. P: the load (4.5 kg) acting on a tooth. For Rm and Rt, see Fig. 2.

i. e., toward the central incisor, and also when the load was applied to the same side as the measuring point. The increase of the strain with the forward movement of the load could be explained by the fact that the moment of the load about the mandibular joint increases and as a consequence the reactions produced at origins of the temporalis and masseter are augmented. But a strain at any point in the lower part of maxilla had a tendency that its magnitude

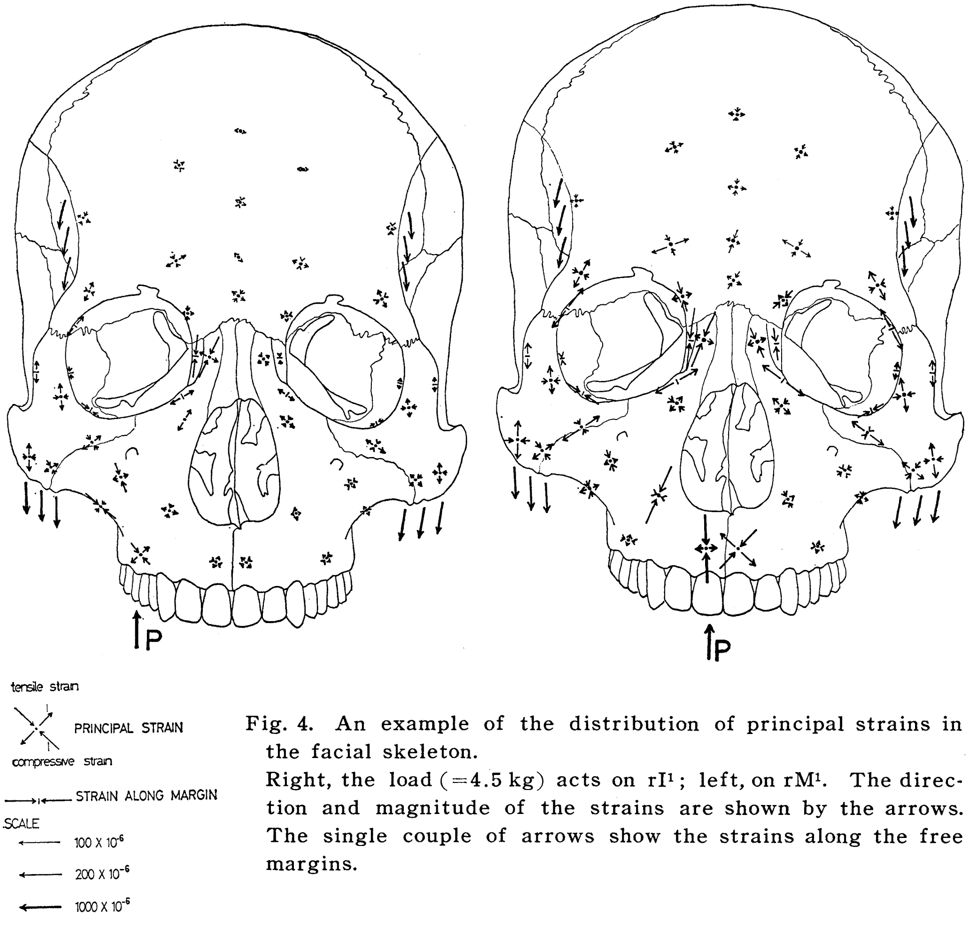


Fig. 4. An example of the distribution of principal strains in the facial skeleton.
Right, the load (=4.5 kg) acts on rI^1; left, on rM^1. The direction and magnitude of the strains are shown by the arrows. The single couple of arrows show the strains along the free margins.

became highest when the load acted on the tooth nearest to the measuring point. These phenomena observed in an exemplary case are shown in Fig. 3.

Fig. 4 illustrates the distribution of principal strains obtained from a specimen: right, caused by loading on the right central incisor; left, by loading the right first molar. The strain designated by a pair of arrows in the figure are along the free margins of the facial skeleton. The actual measurements were made along lines 3 mm apart from and parallel to the margins. The magnitudes of the strains in various points of a facial skeleton differed considerably. In general, strains of high magnitude appeared in such regions as the lower part of the maxilla near the loaded tooth; nasal root; medial end of the infraorbital margin; infero-lateral corner of the orbit; region adjacent to the origin of the masseter; and orbital margin of the zygomatic process of the frontal bone.

The axis of the principal strains was not constant, but its direction varied in different tooth to which the load was applied. The direction of the axes in

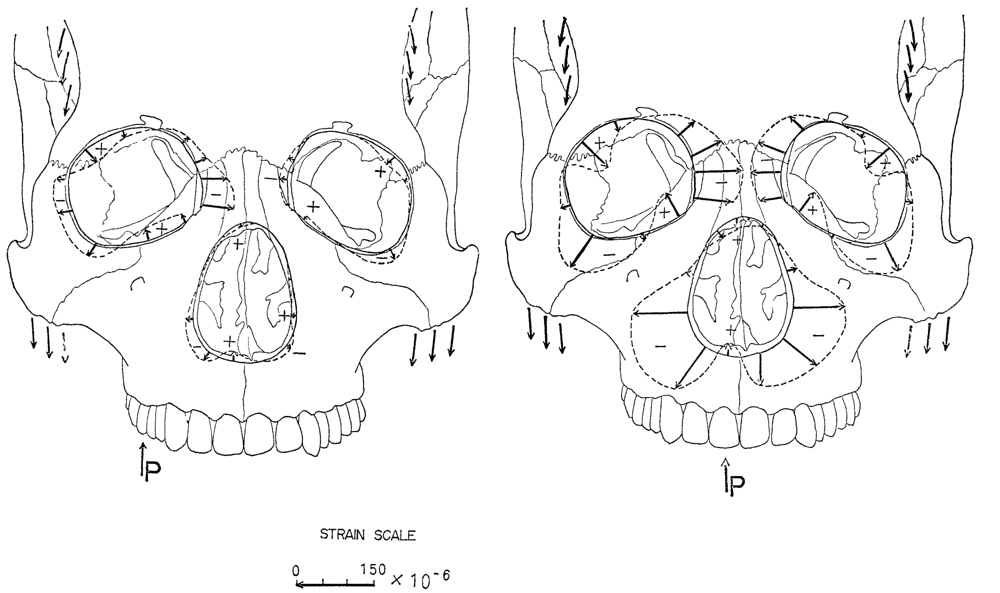


Fig. 5. An example of the distribution of strains along the contour lines of the orbit and the piriform aperture.
Right, the load (=4.5 kg) acts on rI^1: left, on rM^1. The magnitude of strain is shown by the arrow. The lines connecting the root of the arrows show the line along which the strains were measured. + = tensile strain, − = compressive.

the lower part of maxilla especially varied remarkably. Their rotation angle due to the shift of the load from rM^2 to lM^2 became more than 120 degree. On the other hand, the rotation angle of the strain in the other parts of the facial skeleton was usually 15～50 degree.

Fig. 5 exemplifies the distribution of strains along the contour lines of the orbit and the piriform aperture. Actually, in the former case strains were measured along the line 3 mm inside of the orbit and in the latter case 3 mm outside of the aperture. The ordinate of the strains along the margin of the piriform aperture was found to have four peaks, i.e., at lower part of the right and left lateral margins and at superior and inferior margins. The upper and lower peaks deviated slightly toward the loaded side. The lateral peaks were compressive and the upper and the lower peaks tensile. The magnitude of the strain along the lower part of the lateral margin of the loaded side was considerably high as compared with the strains in th other parts of the facial skeleton when any of the anterior teeth was loaded.

Distribution patterns of the strains along the margin of the orbit were found to have also four peaks at lateral part of the superior margin, infero-lateral corner, medial end of the inferior margin and middle part of the medial margin. The first and the third peaks were tensile while the second and the fourth were

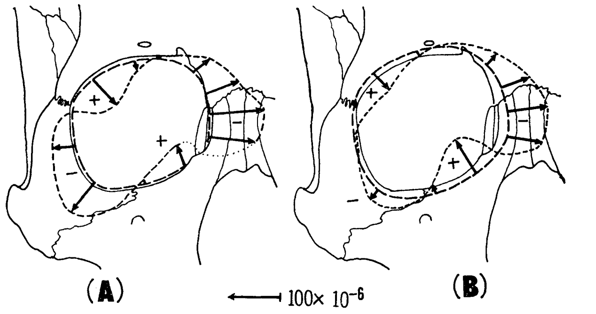


Fig. 6. An example of the distribution of strains around the orbit.
(A) strains along the line 3 mm inside of the orbit, (B) along the line 3 mm outside of the orbit. The big broken lines are the above lines, the fine broken lines are the ordinates. The arrows show the magnitude of strain.

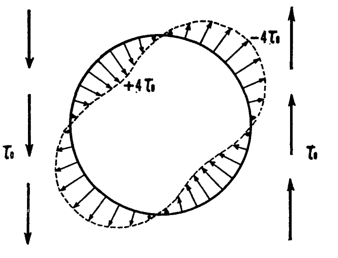


Fig. 7. Stresses along the contour line of the round hole of a infinite plate produced by a shearing force.

compressive. The magnitude of the strains at those peaks were relatively remarkable among the strains in various parts of the facial skeleton. The strains along the line 3 mm outside of the orbit (Fig. 6 (B)) were a little different from those along the line 3 mm inside of the orbit (Fig. 6 (A)). The peaks of the former at the medial end of the inferior margin increased because of the fadeout of the influence of the nasolacrimal canal, and the other peaks decreased as compared with those of the latter. Taking both distribution patterns into consideration, among the absolute values of the magnitudes of the peaks that of the medial peak was a little higher and the others were nearly the same. The distribution pattern of stress or strain of this kind can be deduced easily from the theory of elasticity. Fig. 7 shows the distribution of stresses along the contuor line

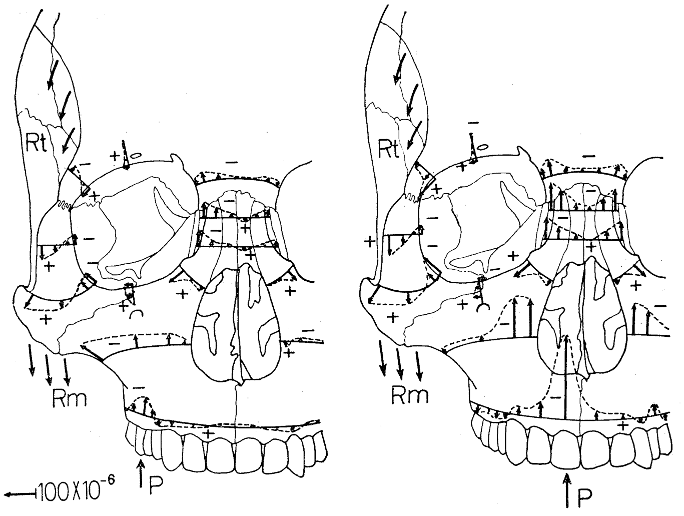


Fig. 8. An example of the normal strains over supposed cross sections in the facial skeleton.
Right, the load (4.5 kg) acts on rI^1; left, on rM^1. The arrows show the directions and magnitudes of the strains. The lines connecting the roots of the arrows are supposed cross sections. + = tensile strain, − = compressive.

of a round hole of a infinite plate which is acted on by a shearing force. The shape of the ordinate in this figure is very similar to that of Fig. 6. Therefore, the strains around the orbit may be produced by a shear which acts upward in the medial part and downward in the lateral part of the facial skeleton.

The normal (vertical) strains were measured over the margin of supposed cross sections in various parts of the facial skeleton. Fig. 8 illustrates the results thus obtained from a specimen. In the Figure the arrows show the direction and magnitude of the strains: + = tensile, − = compressive. The lines connecting roots of the arrows demonstrate the supposed cross sections. In the lower part of the maxilla intensive strains occurred in a restricted region adjacent to the loaded tooth. But in the zygomatic and nasal areas the ordinates of strains rather betoken the remarkable occurrence of the bending moments. As seen in Fig. 9, the zygomatic process of the frontal bone was bent to make convexity toward inside of the orbit (see Z_1–section) and the zygomatic bone was bent buldging toward outside (see Z_2–section). These sections may also be acted on by some axial forces.

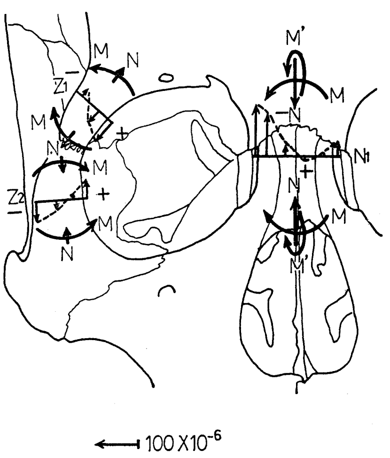


Fig. 9. Bending moments and axial forces acting on the supposed cross sections N_1, Z_1, and Z_2 in the facial skeleton.
M = bending moment about the axis vertical to the paper plane, M′ = bending moment about the axis parallel to the paper plane, N = axial force. The load P (=4.5 kg) acts on rC.

The nasal root was bent protruding antero-laterally (see N_1–section). The direction of this bend rotated with the shift of the load along the dental arch. A couple of moment which causes such bending can be analysed into two kinds, that is, the bending moment about saggital axis (M) and that about transverse axis (M′). In the nasal root a fairly strong axial force may also occur. Strains near the superior and inferior margins of the orbit, seen in Fig. 8, may also suggest the occurrence of the bending moments. Taking all these consideration into account, the mechanical behavior of the facial skeleton might be close to that of the rigid frame structure.

The maximum absolut values of strains in various parts of the facial skeleton obtained in the course of the loading on each of all the teeth were recorded in five cases in order to obtain the relative strength of the various parts. The values at the same point on these specimens were averaged. The magnitude of strain was classified into five grades as shown in Fig. 10. The weakest region

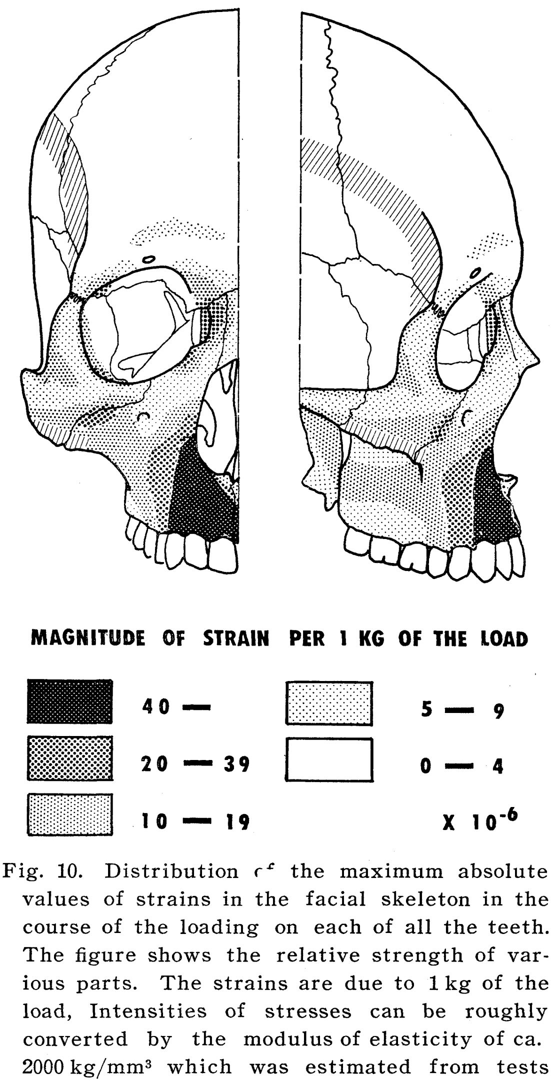


Fig. 10. Distribution of the maximum absolute values of strains in the facial skeleton in the course of the loading on each of all the teeth. The figure shows the relative strength of various parts. The strains are due to 1 kg of the load, Intensities of stresses can be roughly converted by the modulus of elasticity of ca. 2000 kg/mm^3 which was estimated from tests of tibiae accompanied with the skulls used in the experiment. Hatched areas show the attached regions of canvas sheets corresponding to the temporalis and the masseter muscles. The figure is based on strains on 52 points in right half of the facial skeleton.

was the infero-anterior part of maxilla, especially the alveolar processes for foreteeth. The regions of the next rank were found in the following areas: the region around the above; posterior part of the frontal process of the maxilla; medial end of the infraorbital margin; infero-lateral corner of the orbit and its inferior vicinity; and the orbital surface of the zygomatic process of the frontal bone. The medium magnitudes of strain were distributed fairly widely in the maxilla, around the orit, along the margins of the zygomatic bone, and in the pterygoid process. The magnitude of strains in the frontal bone exept the supraorbital margin and superciliary arch were very low.

Fig. 11 exemplifies the distribution of the maximum absolute values of principal strains in the lower part of maxilla obtained in the course of the loading on each of all the teeth. The strains were measured at the bottom of each arrow in the figure. The lower graph in the figure also shows that the alveolar part of the foreteeth is weak and that of the molars is strong. The upper graph represents the same pattern of distribution with smaller scale on the body of maxilla. The strains *a* and *b* in the figure show their maximum values when the load is applied on the canine and the first molar, respectively. The ratio of the strain *a* versus *b* is 3.5 on average of all specimen. However, the moment about the mandibular joint when the load is applied on the canine is on average 1.5 times as that when the first molar is loaded. This discrepancy was statistically significant. The above and the previous facts prove that the anterior region of the lower part of the maxilla makes the weakest area in the facial skeleton when all teeth are used uniformely.

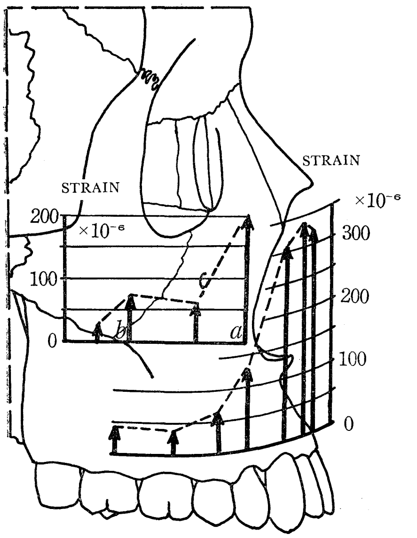


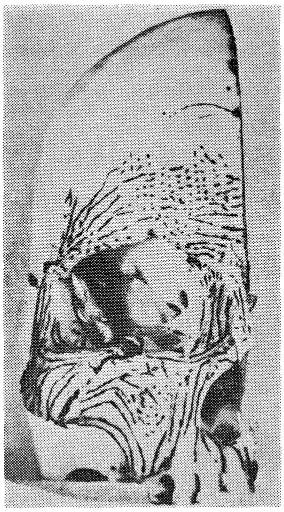
Fig. 11. An example of the distribution of the maximum absolute values of the principal strains in the lower part of the maxilla. At the bottom of the arrows the strains were measured. The strains are due to the load (=4.5 kg) on any of teeth. The magnitude of strain is shown by the ordinates. *a* and *b* see in text.

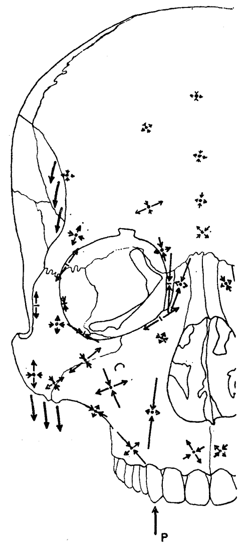
DISCUSSION

It was asserted by PAUWELS (1950) and EVANS and GOFF (1957) that there is little relation between the stress trajectories and the split-lines in the bone. Although the split-lines may look similar to the stress trajectories at a glance, marked differences between these two can be pointed out. For example, the former is linear while the latter is biaxial on the surface. Nevertheless, TAPPEN (1964) persisted in the existence of some positive relationship between the split-lines and the mechanical force. According to his maintenance, alternative explanations of the split-lines proposed by other authors are uncertain when seen from his experiments.

In the facial skeleton the direction of the axis of the principal strain which is identical with the direction of the principal stress changes with the shift of the load along the dental arch. In a living body different set of teeth comes in action in accordance with size and quality of the food and with the stage of crushing process. Accordingly, the stress trajectories are variable in the facial skeleton of the living body, while the split-lines are fixed. The changes of the direction of the axes in the facial skeleton excluding the lower part of the maxilla, however, are relatively small and, in general, their directions seem somewhat to resemble the orientation of the split-lines as shown in Fig. 12. It might be surmized, therefore, that the stress trajectories exert any influence over the formation of the split-line patterns in the facial skeleton, although both the phenomena do not exactly coincide.

From the fact that the fibre strain in the various parts of the facial skeleton exclussive of the lower part of the maxilla suggested the remarkable occurrence





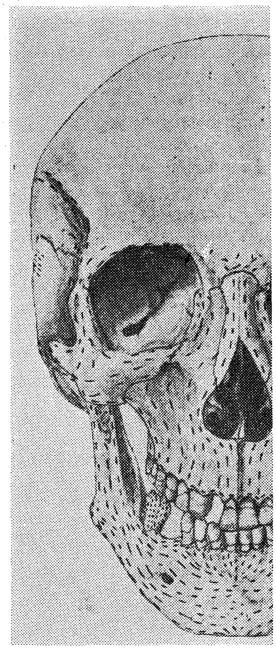


Fig. 12. Comparison between the distribution of principal strains (middle) and the split-line patterns (right, from Benninghoff 1925; left, from TAPPEN 1953) in the facial skeleton.

The right figure shows only right half of the original and the left is a turned-over photograph of the original in order to compare with the middle figure. The middle is the distribution when the load acts on rC.

of the bending moments as seen in Figg. 8 and 9, it could be infered that the main mechanical factor exerting over the facial skeleton may be the bending moment. This agrees with the argument on the long bone by PAUWELS (1948).

The fact that strains in the frontal bone excluding its lower margin are relatively smaller than those in the facial skeleton seems to suggest that the cranial vault plays a role as the protector for the brain rather than the structure resisting the chewing force.

It is evidenced that the infero-anterior part of the maxilla is relatively weaker than the infero-posterior part, even if the change of the moment of the biting force about the mandibular joint is taken into consideration. Accordingly, the human facial skeleton may be more adapted to chew with posterior teeth than to bite with anterior teeth, as has been pointed out by GÖRKE (loc. cit.) and others.

SUMMARY

In an attempt to make analysis of stress and strain on the human facial skeleton due to chewing force, a series of experiments were carried out on dry skulls reproducing the mastication, Brief results are shown in Fig. 4 (ditribution

of principal strains); Fig. 5 (distribution of strains along the free margins); Fig. 8 (distribution of strain normal to the supposed cross sections); and Fig. 10 (distribution of the maximum absolute values of the strains, i. e., relative strength of various parts), and they are summarized as follows:

1) The strains in the facial skeleton increase generally as the load (Pd in Fig. 2 (A)) moves toward the foreteeth in consequence of the increase of the moment of the load about the mandibular joint.

2) The direction of the axes of the principal strains changed according to the shift of the load along the dental arch. Nevertheless, the directions in the facial skeleton excluding the lower part of the maxilla and the forehead, are in some measure similar to the orientation of the split-lines.

3) Intensive strains appear in the anterior region of the lower part of the maxilla. Fairly intensive strains appear in such region as the nasal root, medial end of the infraorbital margin, infero-lateral corner of the orbit and its inferior vicinity, and the orbital surface of the zygomatic process of the frontal bone.

4) Strains in the facial skeleton show the remarkable occurrence of the bending moments.

5) The mechanical behavior of the human facial skeleton seems to resemble that of the rigid frame structure.

6) The infero-anterior part of the maxilla is relatively weak among various parts of the facial skeleton. This fact may suggest that the human facial skeleton is rather adapted to the use of the posterior teeth.

The present study was carried out in the Department of Anthropology, Faculty of Science, University of Tokyo, before the author was transfered to the present institution. The author is deeply grateful to Professor Hisashi SUZUKI of the above department for his guidance and continuous suggestion during the course of the present study. The author also wishes to express his sincere thanks to Professor Teruyoshi UTOGUCHI, Assistant Professor Hiroyuki OKAMURA, and Mr. Shunsaku MITSUHASHI of the Department of Mechanical Engineering, Faculty of Technology, University of Tokyo for their instructive advice during the experiment of the present study.

LITERATURE CITED

BENNINGHOFF, A., 1925: Spaltlinien am Knochen, eine Methode zur Ermittlung der Architektur platter Knochen. Anat. Anz., (Ergänzhefte) Bd. 60: 189–206.

BLUNTSCHLI, H., 1926: Rückwirkung des Kieferapparatus auf den Gesammtschädel. Z. Zahnartztl. Orthoped., Jhg. 18: 57–79.

ENDO, B., 1960: On the stress distribution in the human facial skeleton produced by the occlusion. Proc. Joint Meet. Anthrop. Soc. Nippon & Jap. Soc. Ethn., 14 th Session: 160–162, (in Japanese).

———, 1961: An experiment on the stresses in the facial skeleton due to the chewing action. Proc. Joint Meet. Anthrop. Soc. Nippon & Jap. Soc. Ethn., 15th Session: 19–21, (in Japanese).

———, (in press) Experimental studies on the mechanical significance of the form of the human facial skeleton. J. Fac. Sc. Univ. Tokyo, Sec. 5.

EVANS, F. G. and M. LEBOW, 1951: Regional differences in some of the physical properties of the human femur. J. Appl. Physiol., v. 3, n. 9: 563–572.

EVANS, F. G. and C. GOFF, 1957: A comparative study of the primate femur by means of the stresscoat and the split-line techniques. Am. J. Phys. Anthrop., v. 15: 59–89.

GÖRKE, O., 1904: Beitrag zur funktionellen Gestaltung des Schädels bei den Anthropomorphen und Menschen durch Untersuchung mit Röntgenstrahlen. Arcn. Anthrop., Bd. 1: 91–108.

KO, R., 1953: The tension test upon the compact substance of the long bones of human extremities. J. Kyoto Pref. Med. Univ., v. 53, n. 4: 503–525, (in Japanese with English summary).

PAUWELS, F., 1948: Die Bedeutung der Bauprinzipien des Stütz- und Bewegungsapparates für die Beanspruchung der Röhrenknochen. Z. Anat., Bd. 114: 129–166.

———, 1950: Über die mechanische Bedeutung der gröberen Kortikalisstruktur beim normalen und pathologisch verbogenen Röhrenknochen. Anat. Nachricht., Bd. 1:53–67.

RICHTER, W., 1920: Der Obergesichtsschädel des Menschen als Gebissturm, ein statisches Kunstwerk. D. Mschr. Zahnhlkd., Jhg. 38, H. 2: 49–68.

SICHER, H. and J. TANDLER, 1928: Anatomie für Zahnärtzte. J. Springer. Vienna.

TAPPEN, N. C., 1953: A functional analysis of the facial skeleton with split-line technique. Am. J. phys. Anthrop., v. 11: 503–532.

———, 1954: A comparative functional analysis of primate skulls by the split-line technique. Hum. Biol., v. 26: 220–238.

———, 1964: An examination of alternative explanations of split-line orientation in compact bone. Am. J. Phys. Anthrop. v. 22: 423–441.

YOKOO, S., 1952: The compression test upon the diaphysis and the compact substance of the long bone of human extremities. J. Kyoto Pref. Med. Univ. v. 51, n. 3: 291–313, (in Japanese with English summary).

Department of Oral Anatomy
School of Dentistry
Tokyo Medical and Dental University

ヒトの顔面頭骨における咀嚼時の応力・歪の分布

遠　藤　萬　里

ヒトの顔面頭骨における機能と形態との関係は古くから議論されてきたが，その大部分は想像の域を脱していない。GÖRKE (1902)および RICHTER (1920)は頭骨のX線写真により，BENNINGHOFF (1925)，TAPPEN (1953) らは割線法 (split-line technique) により顔面頭骨における応力線の走向，分布あるいは咬合力に抵抗する基本構造の推定を試みた。しかし割線と応力線とが一致するという見解はPAUWELS (1950)，EVANS and GOFF (1957) らによつて否定されている。また頭骨においてはX線写真により応力線や基本構造を推定することは不可能に近い。ここにおいて，筆者は力学的実験により得られる歪をもちいて応力解析を行い，この問題を解明することを試みた。本論文は上記の問題に関する筆者の研究の一部をなすものであり，とくにヒトの顔面頭骨における咬合時応力の特徴について記載することを目的としたものである。顔面頭骨に関する生体力学上の諸問題の検討は次の論文（印刷中）にゆずることにする。

資料は東京都江東区深川にある浄心寺出土の近世日本人頭骨 21 個体である。これらの頭骨は生体における咬合作用を力学的に近似再現させる装置に取付けられて荷重され，その際生ずる歪が測定された。

結果は主として第4図（主歪の分布），第5図（周歪の分布），第8図（各種仮想断面の縦歪の分布）第10図（歪の最大絶対値の分布ー相対強度図）に示されている。結果を要約すれば下記の通りである。

1) 顔面頭骨における歪は咬合力に相当する荷重が歯列上を前進するにつれて増大する。この現象は顎関節に関する荷重のモーメントの増大によるものである。
2) 顔面頭骨に分布する主歪の軸方向は荷重される歯の交代により変る。しかし，それにもかかわらず，前頭部と上顎下部を除く各部の主歪方向の分布は割線 (split-line) の排列に多少類似するところがある。
3) 最も強い歪は上顎前下部に生ずる。次いで強い歪は鼻根部，眼窩下像内側端，同下外側隅とその下方の頬骨，前頭骨頬骨突起の眼窩面に生ずる。前頭骨の歪はその下縁附近のものを除き一般に非常に小さい。
4) 歪の分布状態からみて，顔面頭骨各部には著るしい曲げモーメントが生じていることが分る。この事実から，顔面頭骨に及ぼす力学的影響の主たるものは曲げモーメントであると考えることができる。
5) 上顎前下部は他の部分に比べて非常に弱い。この事実はヒトの顔面頭骨がむしろ臼歯を使用して咀嚼することに適応していることを示すものであろう。

（東京医科歯科大学歯学部口腔解剖学教室）