Stress distributions in the maxillary complex from orthopedic headgear forces

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Orthopedic headgear therapy has been applied to growing patients who have various skeletal discrepancies due to a large and/or anteriorly-positioned maxilla. For treatment involving the correction of skeletal relationships between the maxilla and mandible, it is important to understand the responses of the craniofacial skeleton to orthopedic forces.

Various studies have been conducted to elucidate morphological, biological and biomechanical changes of the complex incident to orthopedic headgear treatment. Cephalometric studies have revealed morphological alterations of the skeleton and redirection of maxillary growth. These changes vary with different directions of orthopedic headger forces.[1-5] Animal experiments have also demonstrated sutural modifications produced by orthopedic headgear forces applied to the maxillary complex.[5-9] Further, various measuring methods such as the strain gauge, and photoelastic and laser holographic techniques have described the nature of stress and/or strain distributions in the bony structures.[10-14] This may be the key to biological remodeling of the complex.

These findings are useful for determining the optimal force applications for headgear therapy. Further elucidation of biomechanical behavior of the complex, and more specifically, sutural responses to headgear forces, is still needed. The majority of previous studies are limited in their evaluation of stress distributions in the internal structures, including the sutures, of the craniofacial complex. Thus, because of difficulties in measuring strains and stresses in living tissues, the

Abstract

The present study was conducted to investigate stress distributions in the maxillary complex from headgear forces by means of three-dimensional finite element analysis. A posteriorly-directed force of 1.0 Kgf was applied to the maxillary first molars in the directions parallel and 30 degrees inferior to the occlusal plane.

In the lower regions resisting posterior displacement of the complex, large normal and shear stresses were observed. Meanwhile, the regions resisting upward displacement experienced larger than normal stresses. A downward force produced slightly larger stresses than a parallel force and varied the nature of stresses from compressive to tensile or vice versa in the temporozygomatic suture. Thus, the stress distributions in the sutures varied according to their anatomic locations relative to force directions.

The maxillary complex exhibits postero-inferior displacement with clockwise rotation from the horizontal headgear force. This becomes more prominent as the direction of force becomes more inferior.

Key Words

Headgear • Biomechanics • Stress distribution • Suture • Finite element analysis

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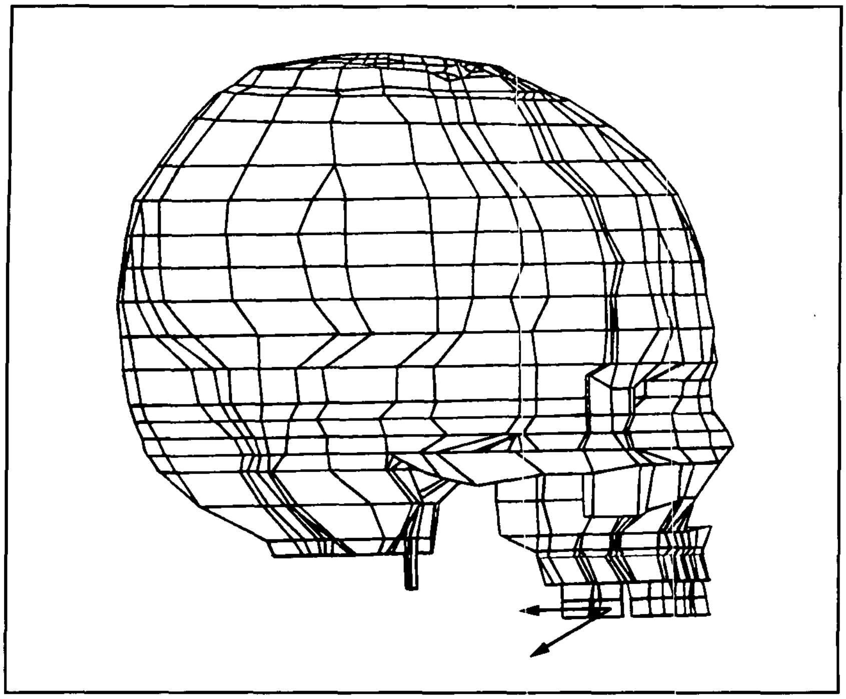

Figure 1

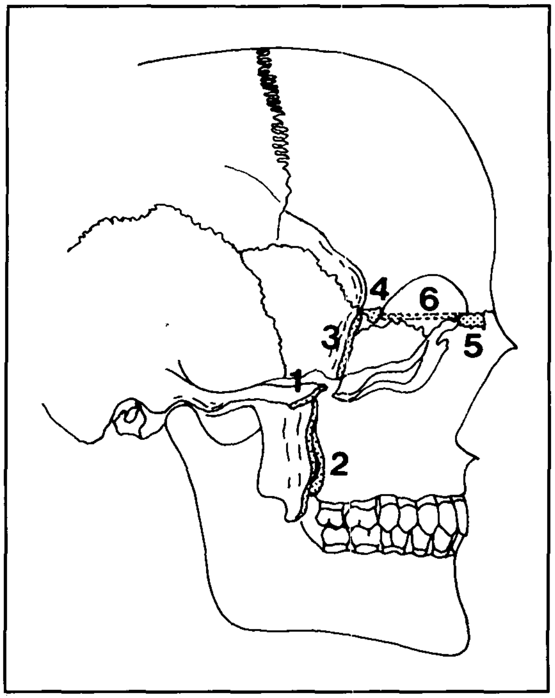

Figure 2

Table 1 Mechanical properties of the tooth and compact and cancellous bones		
Material	Young's modulus (kgf/mm^2)	Poisson's ratio
Tooth	2.07 x 10^3	0.30
Compact bone	1.37 x 10^3	0.30
Cancellous bone	8.00 x 10^2	0.30

Figure 1
Three-dimensional model of the human craniofacial complex. The model consists of 2918 nodes and 1776 solid elements. Eighteen sutural systems are integrated in the model. Arrows denote the directions of headgear forces, parallel and 30 degrees downward to the occlusal plane.

Figure 2
Six anatomic regions where stress distributions are investigated:
1) temporozygomatic suture
2) sphenomaxillary suture
3) sphenozygomatic suture
4) frontozygomatic suture
5) frontomaxillary suture
6) lamina cribosa

detailed patterns of stress distributions in the complex--in the sutural system in particular--have not been fully elucidated. On the other hand, the finite element method (FEM) makes it possible to elucidate biomechanical components such as strains and stresses induced in the living structures from various external forces.[15-18]

The purpose of this study was to investigate biomechanical responses of the maxillary dentition by means of three-dimensional finite element analysis.

Materials and methods

A three-dimensional model of the craniofacial complex was used in this study. The analytic model was developed from the dry skull of a young human. Fourteen transverse sections of the skull were cut at approximately 10 mm intervals parallel to Frankfort horizontal plane. Photographs of both dorsal and ventral aspects were taken of each section at one-to-one magnification. Anatomic structures were precisely traced onto acetate paper. These two-dimensional drawings were divided into a finite number of elements, ensuring that the geometric shape of the model relative to the actual anatomic structures was maintained. Finally, the two-dimensional images of all the sections were stacked perpendicularly to the Frankfort plane and a three-dimensional analytic model was developed. Details of the modeling procedure were described in a previous article.[17] The model consists of 2918 nodes and 1776 elements (Figure 1). Eighteen sutural systems were integrated in the model. The mechanical properties of the components of the model were defined based on previous data[19,20] as shown in Table 1.

Restraints were established at the region around the foramen magnum where no linear and angular displacements were allowed. A posteriorly-directed force of 1.0 Kgf was applied to the maxillary first molars of the model parallel and 30° downward to the functional occlusal plane determined on the maxillary dentition.

Three principal stresses were analyzed. Mean principal and octahedral shear stresses derived

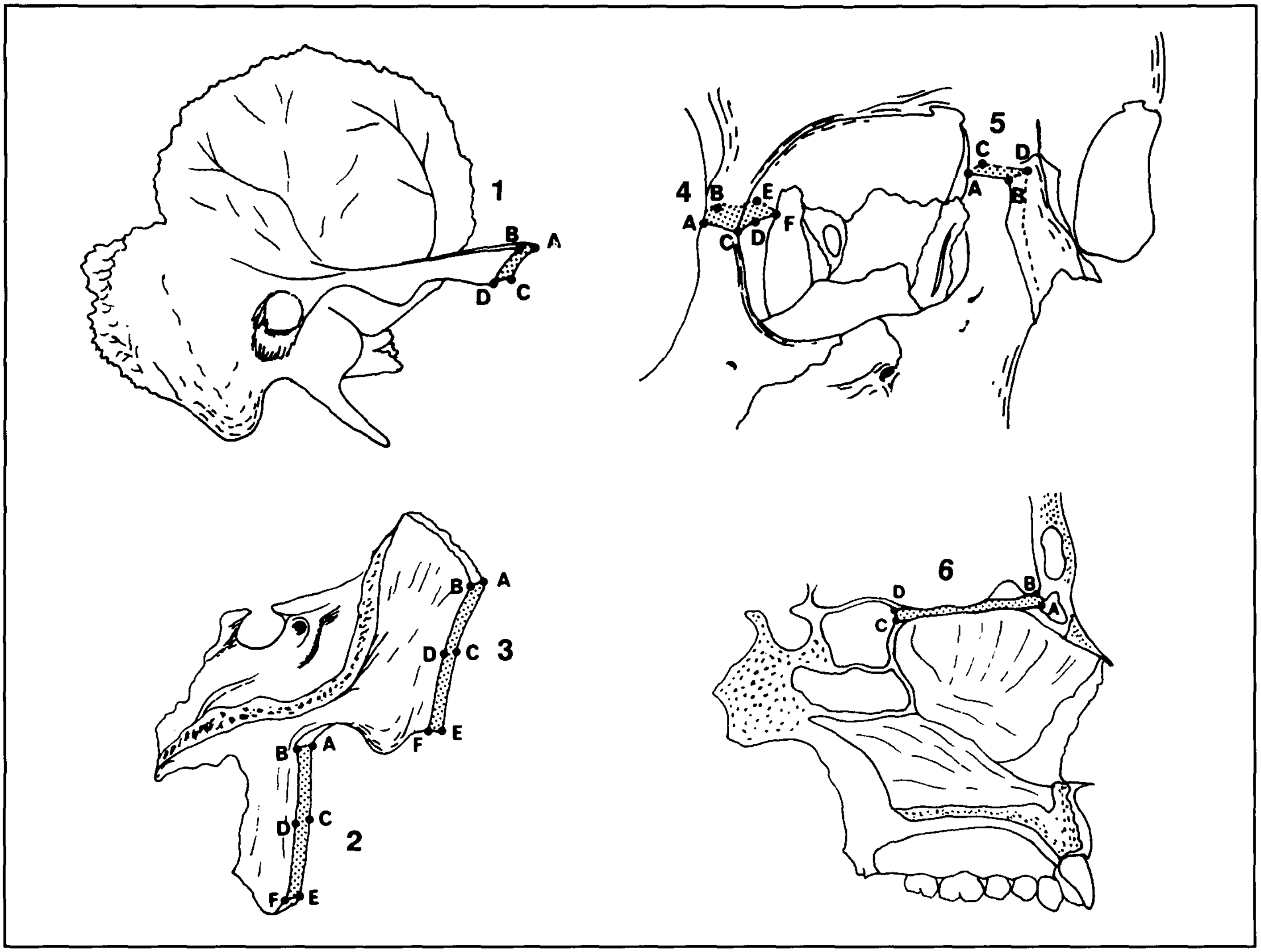

Figure 3

from the three principal stresses were evaluated for each of six regions (Figure 2): temporozygomatic, sphenomaxillary, sphenozygomatic, frontozygomatic, frontomaxillary sutures and lamina cribrosa (Figure 3) to elucidate the biomechanical responses of the complex. Mean principal stress and octahedral shear stress denote hydrostatic pressure or normal stress and deviator stress component,[21] respectively.

Results

Normal stress, produced by the parallel headgear force to the occlusal plane, ranged from -25.6 gf/mm^2 at the medioinferior point (E) of the sphenomaxillary suture to 14.3 gf/mm^2 at the posterolateral point (A) of the frontomaxillary suture. Meanwhile, shear stress varied from 1.4 gf/mm^2 at the medioinferior point (C) of the temporozygomatic suture to 31.0 gf/mm^2 at the medioinferior point (E) of the sphenomaxillary suture. These results demonstrated that headgear forces could be transmitted widely to distant

Figure 3
Schematic representation of the six anatomic regions shown in Figure 2. For each of the regions, four or six points are defined to evaluate stress distributions.

1) **temporozygomatic suture: A) mediosuperior point, B) laterosuperior, point, C) medioinferior point, D) lateroinferior point.**
2) **sphenomaxillary suture: A) mediosuperior point, B) laterosuperior point C) mediomiddle point, D) lateromiddle point, E) medioinferior point, F) lateroinferior point.**
3) **sphenozygomatic suture: A) mediosuperior point, B) laterosuperior point C) mediomiddle point, D) lateromiddle point, E) medioinferior point, F) lateroinferior point.**
4) **frontozygomatic suture: A) anterolateral point, B) posterolateral point, C) anteromedial point, D) posteromedial point, E) lateral point adjacent to the greater wing, F) medial point adjacent to the greater wing.**
5) **frontomaxillary suture: A) posterolateral point, B) anterolateral point, C) posteromedial point, D) anteromedial point.**
6) **lamina cribosa: A) anteromedial point, B) anterolateral point, C) posteromedial point, D) posterolateral point.**

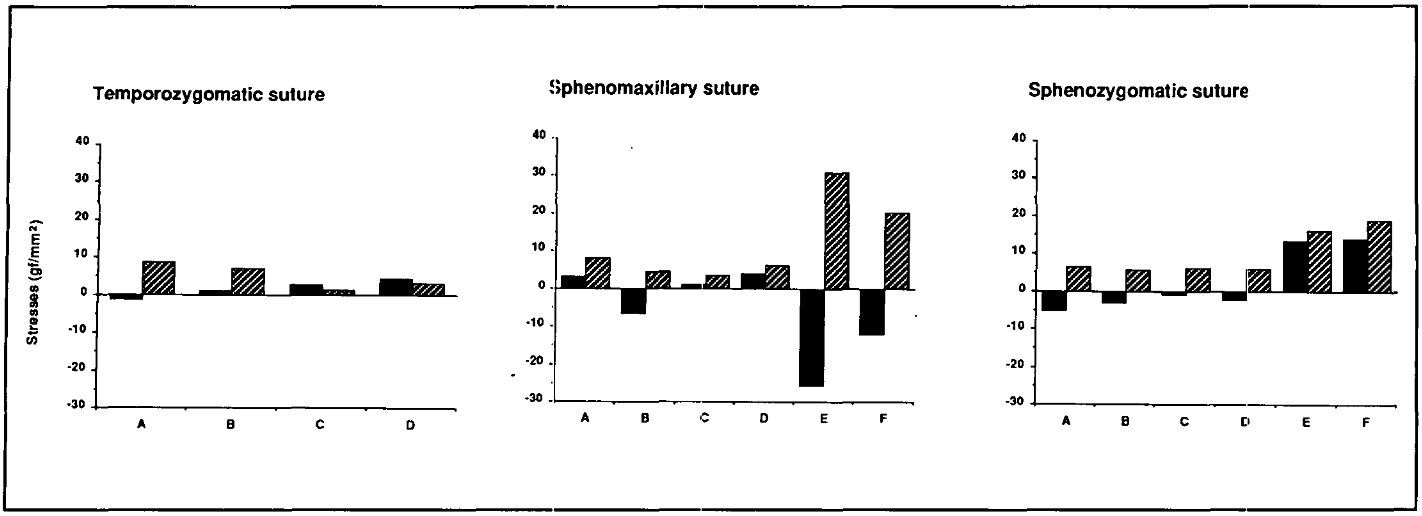

Figure 4

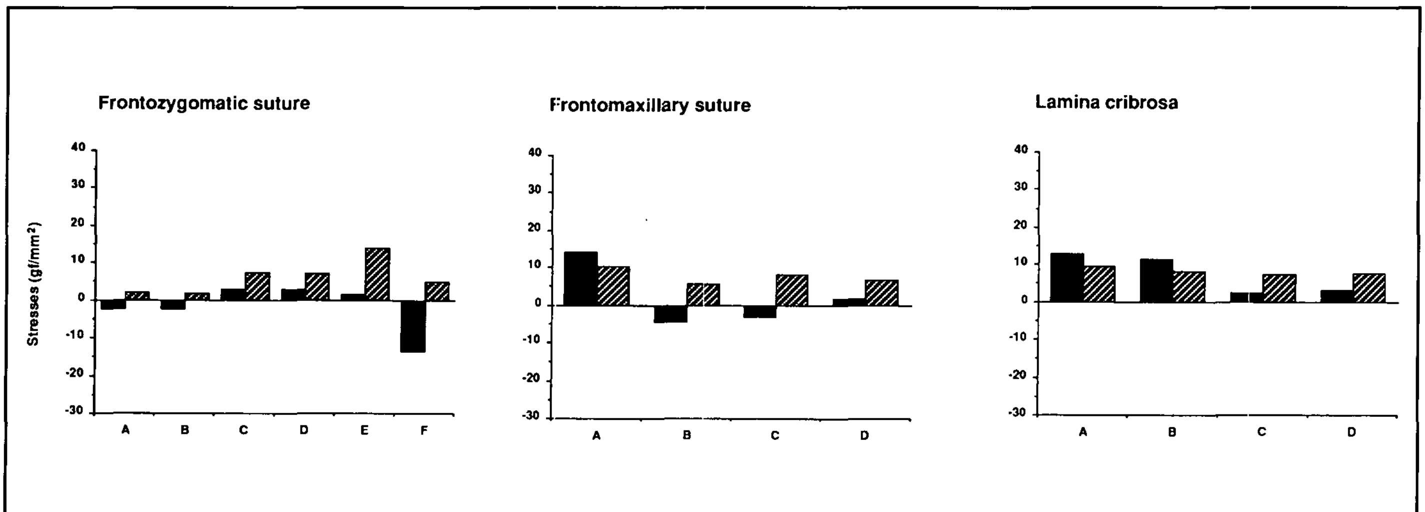

Figure 5

Figure 4
Stress distributions in the anatomic regions resisting posterior displacement of the complex. (A) through (F) denote the anatomic points described in Fig. 3.
■ principal stress
▨ shear stress

Figure 5
Stress distributions in the anatomic regions resisting upward displacement of the complex. (A) through (F) denote the anatomic points described in Fig. 3.
■ principal stress
▨ shear stress

craniofacial sites.

Stress distributions in the anatomic regions resisting the horizontal displacement of the complex are shown in Figure 4.

For most of the anatomic points A through D around the temporozygomatic suture, tensile normal stresses were observed, ranging in the magnitude from 1.0 to 4.5 gf/mm^2, whereas slight compressive stress of -1.0 gf/mm^2 was induced at the mediosuperior point (A). Shear stresses were larger than normal stresses in the superior areas (A and B) and smaller in the inferior area (C and D).

For the sphenomaxillary suture, large compressive stresses were induced in the laterosuperior (B) and inferior areas (E and F), in particular greatest compressive stress of -25.6 gf/mm^2 was observed at the medioinferior point (E). Meanwhile, tensile stresses were produced in the mediosuperior (A) and middle areas (C and D). Shear stresses were larger in most of the regions than normal stresses and the finding was prominent in the inferior area (E and F).

For the sphenozygomatic suture, slight compressive stresses were observed in the superior and middle areas (A through D), whereas large tensile stresses of approximately 13.0 gf/mm^2 were produced at the inferior points (E and F). Shear stresses were also prominent in the inferior region (E and F).

Stress distributions in the anatomic regions resisting the vertical displacement of the complex are shown in Figure 5.

For the frontozygomatic suture, large compressive stress of -13.5 gf/mm^2 was induced in the medial area (F) adjacent to the greater wing of sphenoid bone. Meanwhile, slight tensile stresses of approximately 3.0 gf/mm^2 were observed in the medial area (C and D) and the lateral area (E) adjacent to the greater wing of sphenoid bone. Shear stresses were larger than or almost similar to normal stresses excluding the medial point (F) adjacent to the greater wing of sphenoid bone. In particular, large shear stress of 14.1 gf/mm^2 was induced at the lateral point (E) close to the greater wing of sphenoid bone.

Table 2
Values of principal (σ-OCT) and shear (τ-OCT) stresses with the downward force and ratios of stresses for the anatomic regions resisting the posterior displacement

Anatomic region	σ-OCT (gf/mm^2) Horizontal (H)	Downward(D)	D/H	τ-OCT (gf/mm^2) Horizontal (H)	Downward(D)	D/H
Temporozygomatic suture						
A	-1.0	8.2	-8.20	8.7	2.4	0.28
B	1.0	4.5	4.50	7.2	2.1	0.29
C	2.7	-7.4	-2.74	1.4	12.7	9.07
D	4.5	-12.3	-2.73	3.2	9.2	2.88
Sphenomaxillary suture						
A	3.3	2.8	0.85	8.3	7.8	0.94
B	-6.7	-6.8	1.01	4.7	4.0	0.85
C	1.2	12.3	10.25	3.6	3.3	0.92
D	4.0	4.1	1.03	6.3	5.6	0.89
E	-25.6	-21.5	0.84	31.0	23.7	0.76
F	-12.0	-11.9	0.99	20.2	16.1	0.80
Sphenozygomatic suture						
A	-5.3	-7.7	1.45	6.5	7.2	1.11
B	-2.9	-2.8	0.97	5.9	6.8	1.15
C	-0.9	-0.2	0.22	6.2	6.6	1.06
D	-2.3	-1.8	0.78	6.1	6.4	1.05
E	13.4	15.0	1.12	16.3	18.2	1.12
F	13.0	14.0	1.08	19.0	20.2	1.06

For the posterolateral point (A) of the frontomaxillary suture, large tensile stress of 14.3 gf/mm^2 was observed, whereas slight compressive stresses were generated at the anterolateral (B) and posteromedial (C) points. The magnitudes of shear stress were almost similar in all the points.

For the lamina cribosa, large tensile stress was induced in the anterior area (A and B), whereas slight tensile stress was observed in the posterior region (C and D). Shear stress presented almost similar patterns in all the points of A through D.

Tables 2 and 3 show the stress values associated with a downward retraction force and the ratios of stresses from the downward force to those from the horizontal force. The downward force produced a slight increase of stress values in comparison with the parallel force and this also varied the nature of normal stresses from compressive to tensile or vice versa in the temporozygomatic suture.

Discussion

Recently, interest in the remodeling of bony structures has grown.[22-27] In clinical orthodontics, a variety of procedures are employed to correct dental and skeletal discrepancies. Remodeling of the alveolar bone as well as the craniofacial complex should be well understood to achieve the optimal correction.

The present study, as a first step of biomechanical investigation, was conducted to elucidate the nature of stress distributions in the sutural systems of the craniofacial complex. The sutures in the maxillary complex were divided into two groups related to how the anatomic location resists horizontal or vertical displacement.[28] This makes it easier to evaluate the response of each sutural system to forces, i.e. if the maxillary complex displaces backward in a translatory manner, the sutures resisting the posterior and upward displacements should exhibit substantial normal and shear stresses, respectively, with opposite results for upward dis-

Table 3
Values of principal (σ-OCT) and shear (τ-OCT) stresses with the downward force and ratios of stresses for the anatomic regions resisting the upward displacement

Anatomic region	σ-OCT (gf/mm²) Horizontal (H)	σ-OCT (gf/mm²) Downward(D)	D/H	τ-OCT (gf/mm²) Horizontal (H)	τ-OCT (gf/mm²) Downward(D)	D/H
Frontozygomatic suture						
A	-2.1	-2.5	1.19	2.2	2.6	1.18
B	-2.1	-2.2	1.05	2.0	2.2	1.10
C	3.1	3.8	1.23	7.4	8.9	1.20
D	3.0	3.8	1.27	7.2	8.9	1.24
E	1.6	2.6	1.63	14.1	13.5	0.96
F	-13.5	-13.1	0.97	4.9	4.0	0.82
Frontomaxillary suture						
A	14.3	17.9	1.25	10.4	13.1	1.26
B	-4.4	-5.8	1.32	5.9	7.3	1.24
C	-3.1	-3.7	1.19	8.1	10.2	1.26
D	1.9	2.4	1.26	6.8	8.9	1.31
Lamina cribrosa						
A	12.9	15.5	1.20	9.7	11.7	1.21
B	11.6	14.9	1.28	8.3	10.1	1.22
C	2.4	1.2	0.50	7.5	9.1	1.21
D	3.4	2.7	0.79	7.6	9.5	1.25

placement.

In this study orthopedic headgear forces were widely transmitted to distant sutural systems in the craniofacial complex. Large normal stresses were induced with almost the same magnitude of shear stresses in the lower areas of the sutures. The sphenomaxillary and sphenozygomatic sutures, in particular, resisted the posterior displacement of the complex. Larger shear stresses were observed in comparison with normal stresses in areas resisting the upward repositioning of the complex. More downward force produced larger stresses than did horizontal force and this varied the nature of stresses in the temporozygomatic suture. These findings were coincident with previous results[1,3,4,6,7,11,12,17] pertaining to cervical retraction of the maxilla in terms of postero-downward displacement of the complex associated with clockwise rotation. The present study also indicates different stress distributions in the sutural systems according to their anatomic locations relative to force directions. Further, the existence of shear stress in the sutures suggests sliding of the bones at the interface in addition to widening or narrowing of the sutural space denoted by changes in normal stresses, as was indicated by Merrifield and Cross.[29]

In previous studies,[30,31] growth and remodeling of the maxillary complex were investigated extensively. According to these studies 1) the ethmomaxillary complex grows in inferior and anterior directions with periosteal deposition and resorption on the bony surfaces, and 2) sutural deposits are produced in response to such displacements of the complex. Therefore, it may be speculated from the present findings that biomechanical stresses from headgear forces are effective for controlling growth of the complex in patients with a large and/or anteriorly-positioned maxilla if assumed that stresses affect bone remodeling with sutural deposits. With respect to sutural responses to mechanical stresses, tensile and compressive stresses acting at the sutural interfaces produce deposition and resorption of bone facing the interfaces.[6,7,22,23] For the alveolar bone, principal stresses in the PDL were regarded as a key to bone remodeling incident to orthodontic force application.[24,25] Principal stresses are also recognized as an important factor for the remodeling of long bones.[26] From these considerations, octahedral principal and shear stresses were evaluated in this study. In general, whole stress at an arbitrary point in the object consists of these two stress components and thus their evaluation seems easier and more convenient for describing overall stress distributions.[21] Further, it makes possible the prediction of mechanical behavior of bones at the sutural interface, i.e. sliding and repoitioning of the bones in parallel and perpendicular directions to the sutural plane,[29] which are also observed during normal growth of the maxilla.[31]

For headgear therapy, the direction of force relative to the level of center of resistance (CRe) is very important in a biomechanical aspect, as described in biomechanical studies of orthodontic forces.[32,33] The directions of force in the present analysis, which are regarded as cervical traction in a clinical aspect, were substantially below the assumed position of the CRe,[1,3] therefore, great rotation of the complex was produced in addition to posterior repositioning. Since the location of the CRe is still unclear, its determination will be needed for precise application of headgear forces. Further, the biomechanical responses of the complex, the patterns of repositioning and/or sliding of bones at the sutural interfaces, should be investigated in detail for various directions of forces. Such approaches would help achieve optimal results when the use of headgear is indicated.

Conclusions

Stress distributions in the maxillary complex from headgear forces were investigated by means of three-dimensional finite element analysis. An extraoral force of 1.0 Kgf was applied to the maxillary first molars in the posterior direction, parallel and 30 degrees downward to the occlusal plane. Principal and shear stresses were evaluated for six anatomic regions.

The following results were obtained.

1. For the areas resisting posterior displacement of the complex, large normal and shear stresses were observed in the lower regions, especially in the sphenomaxillary and sphenozygomatic sutures.

2. The regions resisiting upward displacement experienced larger than normal stresses.

3. The downward force produced slightly larger stresses than did the horizontal force and also varied the nature of stresses from compressive to tensile or vice versa in the temporozygomatic suture.

These findings show that the stress distributions in the sutures vary in relation to the direction of force. The maxillary complex exhibits posteroinferior displacement with clockwise rotation from the horizontal force. This becomes more obvious as the direction of force becomes more inferior.

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Commentary: Stress distributions from headgear forces

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Different techniques have been used to evaluate the effects of orthopedic forces on the growth of the maxillary complex. The more collaboration we have on this important topic, the clearer these concepts will become for the clinician. This type of excellent research should put to rest the question, in some clinicians' minds, as to whether or not orthopedic force application in orthodontics is a viable concept.

Although the three-dimensional finite element analysis described in this article may be difficult to comprehend without some background in engineering, the conclusions made by the authors are very sound, based on their methodology. Their results become especially relevant when comparing the stress distributions in the sutures and the rotation of the maxillary complex with the various vectors of force. As a result of the research presented in this article, a more thorough understanding has been attained of the orthopedic effects of different "pull" headgears.

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