Association between the direction of orthopedic headgear force and sutural responses in the nasomaxillary complex

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Since Kloehn's[1] interesting study in 1947, orthopedic headgear therapy has been accepted as an effective treatment for growing patients with maxillary excess. Various types of headgear have been developed for clinical use in orthodontics.[2]

Maxillary growth is generated by sutural modification at the interfaces between various bones in the nasomaxillary complex. Considerable variation in growth occurs.[3] The elucidation of the changes produced by headgear forces is important to the understanding of optimal headgear therapy. Cephalometric studies have demonstrated that headgear forces produce significant skeletal changes by decreasing forward and/or downward maxillary growth.[3-8] Animal experiments indicate that orthopedic forces produce primary displacement of the bones in the complex and subsequently initiate bone remodeling at the sutural interfaces, which is regarded as a key to morphological alteration of the entire complex. An analysis or measurement of biomechanical changes in the sutures is the next logical area of investigation. The nature of stress distributions in the sutural interfaces have not been elucidated because direct measurements are impossble without tissue damage. The purpose of this study was to investigate, by means of finite element analysis, biomechanical responses of the nasomaxillary bones at the sutural interfaces to orthopedic headgear forces applied in various directions.

Abstract

This study was designed to investigate biomechanical responses of the sutures in the nasomaxillary complex to orthopedic headgear forces applied in various directions. A three-dimensional analytic model of the craniofacial complex was used for finite element analysis. A posteriorly-directed force of 1.0 Kgf was applied to the maxillary first molars in 30° inferior, parallel, and 30°, 52.4° and 60° superior directions to the functional occlusal plane. Mean principal and shear stresses were evaluated at the sphenozygomatic, temporozygomatic, sphenomaxillary, frontomaxillary and frontozygomatic sutures and lamina cribrosa. As the force direction passed closer to the center of resistance (CRe) of the complex (52.4° superior direction), normal stresses approached a certain level of uniform compressive stress (-2.5 gf/mm^2) with gradual decrease in shear stresses, whereas variation in these stresses produced by the forces applied in other horizontal and inferior directions was greater. It is shown that stresses in the nasomaxillary sutures are varied by the direction of headgear force. Directing the line of force closer to the CRe may produce the most optimal sutural modification effective for controlling forward and downward maxillary growth.

Key words

Orthopedic headgear therapy • Force direction • Center of resistance • Craniofacial suture • Finite element analysis

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Table 1
Mechanical properties of the teeth and compact and cancellous bones

Material	Young's modulus (Kgf/mm^2)	Poisson's ratio
Tooth	2.07×10^3	0.30
Compact bone	1.37×10^3	0.30
Cancellous bone	8.00×10^2	0.30

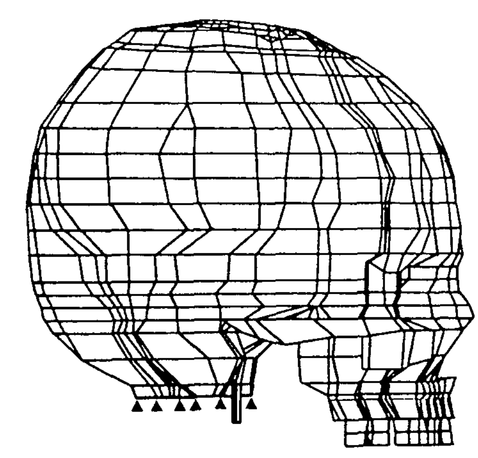

Figure 1

Figure 1
A schematic representation of the model. Solid triangles denote restraints for the model during loading.

Materials and methods

A three-dimensional finite element model of the craniofacial skeleton was employed in this study. The model was developed from the dried skull of a young human and consisted of 2918 nodes and 1776 solid elements[15] (Figure 1). Element discretization, including mesh refinement, was repeatedly modified by means of distortion parameter, which allows a reasonable distortion of element and convergence or accurate analysis. From the viewpoint of geometric equivalence and reasonable element distortion, the model appears to be valid for use in stress analyses.[15] The model includes 18 cranial and facial sutures, comprising the teeth and compact and cancellous bones. The mechanical properties of these components were defined based on previous data,[16,17] as shown in Table 1.

The model was fixed at the area around the foramen magnum to prevent sliding during loading, simulating clinical application of headgear forces. A posteriorly directed 1.0 Kg force was applied to the maxillary first molars in five different directions to the functional occlusal plane; 30° inferior, parallel, and 30°, 52.4°, and 60° superior. A 52.4° superior direction was demonstrated in advance to connect the center of resistance (CRe) of the nasomaxillary complex and the maxillary first molars.[18]

Stress analysis was executed on FACOM computer using an analysis program, FEM5 (Kyoto University Computation Center). Mean principal and shear stresses, converted from three principal stresses, were evaluated for the sphenozygomatic, temporozygomatic, sphenomaxillary, frontomaxillary, and frontozygomatic sutures and lamina cribrosa.

Results

Figure 2 shows stresses in the sphenozygomatic, temporozygomatic, and sphenomaxillary sutures resisting posterior displacement of the nasomaxillary complex. In the superior and medial regions of the sphenozygomatic suture, compressive stresses were induced by the forces applied in all directions. These stresses exhibited similar values in response to force direction. Meanwhile, stresses in the inferior area of the suture were tensile in nature and exhibited a substantial decrease when the force direction became upward.

In the inferior region of the temporozygomatic suture, slight tensile stresses were induced in loading with forces applied in different directions, whereas stresses in the superior area were negligible. The stresses in the the inferior region decreased slightly when the direction was varied from 0° to 60° superior.

In the superior and inferior areas of the sphenomaxillary suture, compressive stresses exhibited substantial decreases in loading with more superiorly directed forces. These changes were more obvious in the inferior region than in the superior. On the other hand, stresses in the medial region were tensile in nature. However, the magnitude was decreased by more superiorly directed forces approaching 52.4° or 60°.

The total amounts of shear stresses at eight anatomic points in three sutures for each of five directions are shown in Figure 3. In loading with a posteriorly directed horizontal force, total shear stress was greatest, indicating the sliding of two adjacent bones and the subsequent substantial shear deformation of the sutural structure associated with counterclockwise rotation of the complex.

An interesting finding was that these stresses decreased substantially when 52.4° or 60° superiorly directed forces were applied. These findings indicate that the minimum shear deformation was generated in the anatomic areas resisting posterior displacement of the complex by the fwo forces.

Figure 4 shows that stresses in the posterior area of the frontozygomatic suture decreased slightly as the direction became upward, although almost uniform compressive stresses were generated irrespective of force direction. Meanwhile, stresses in the remaining points in this suture were tensile in nature during loading with downward and horizontal forces but changed to compressive when more superiorly directed forces were applied.

In the frontomaxillary suture, headgear forces applied in 52.4° and 60° superior directions produced almost uniform compressive and tensile stresses in the anterior and posterior regions, and the nature of stresses became opposite in loading with forces applied in the remaining directions.

In the anterior and posterior areas of the lamina cribrosa, stresses were tensile in most loading cases, although two superiorly directed forces produced slight compressive stresses in the anterior region.

The total amounts of shear stresses at seven anatomic points for each of five directions are shown in Figure 5. When a downward force of 30° was applied, total shear stress was highest, indicating a substantial shear deformation of the sutural structure. An interesting finding was that these stresses decreased gradually when the direction was varied from 30° inferior to 52.4° or 60° superior. These findings indicate that the two loading conditions produced the least shear deformation in the anatomic regions resisting superior displacement of the complex.

Figure 6 shows changes in stress at five points in different anatomic areas that exhibited relatively large stresses associated with varying directions of headgear force. The stresses exhibited gradual increases or decreases approaching a uniform level of compressive stress as the direction was varied from -30° to 60° degrees to the functional occlusal plane. Thus, variation in these stresses decreased and the nature of stresses became more uniform when directing the line of force closer to the CRe of the nasomaxillary complex.

Discussion

From a biomechanical aspect, many variables in the force system are pertinent to displacement

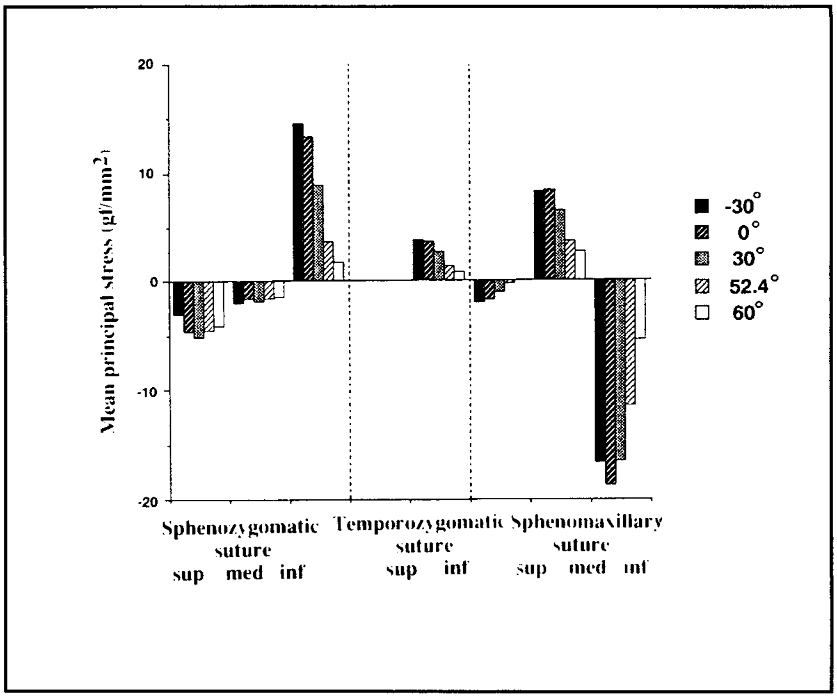

Figure 2

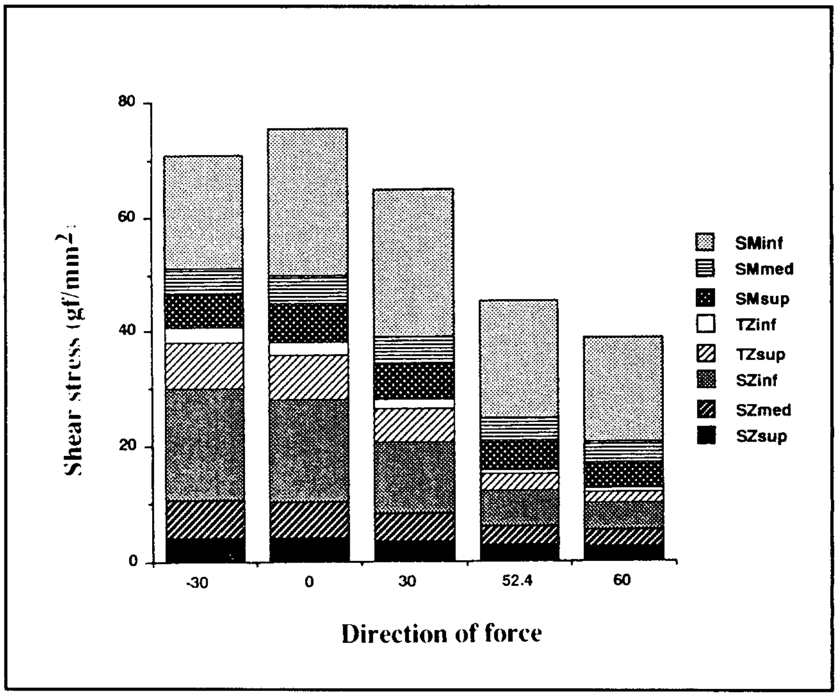

Figure 3

Figure 2
Mean principal stresses in the anatomic areas resisting backward displacement of the complex.

Figure 3
The total amount of shear stresses in the anatomic areas resisting backward displacement of the complex. Shear stress in each area was accumulated for each force application. SM–sphenomaxillary suture; TZ–temporozygomatic suture; SZ–sphenozygomatic suture.

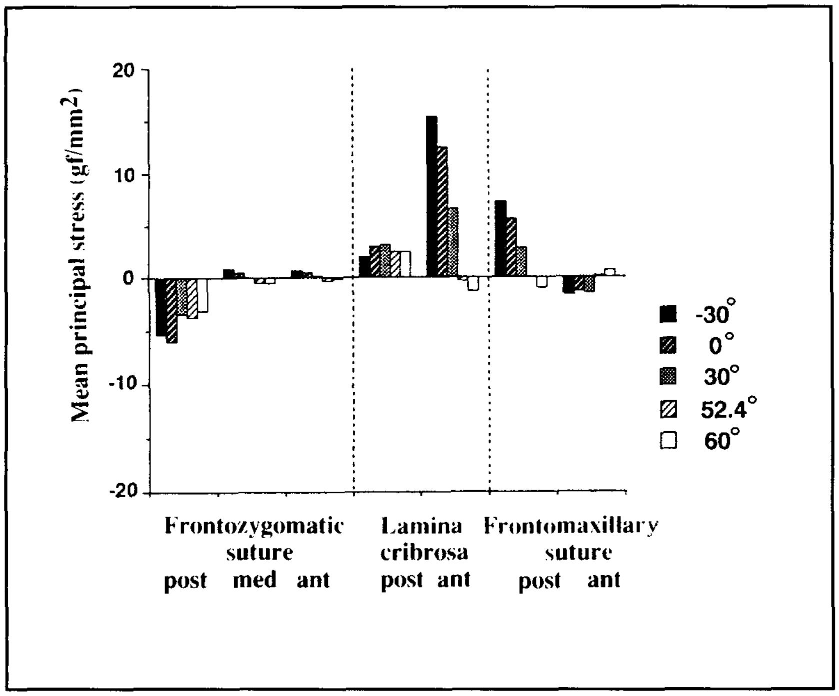

Figure 4

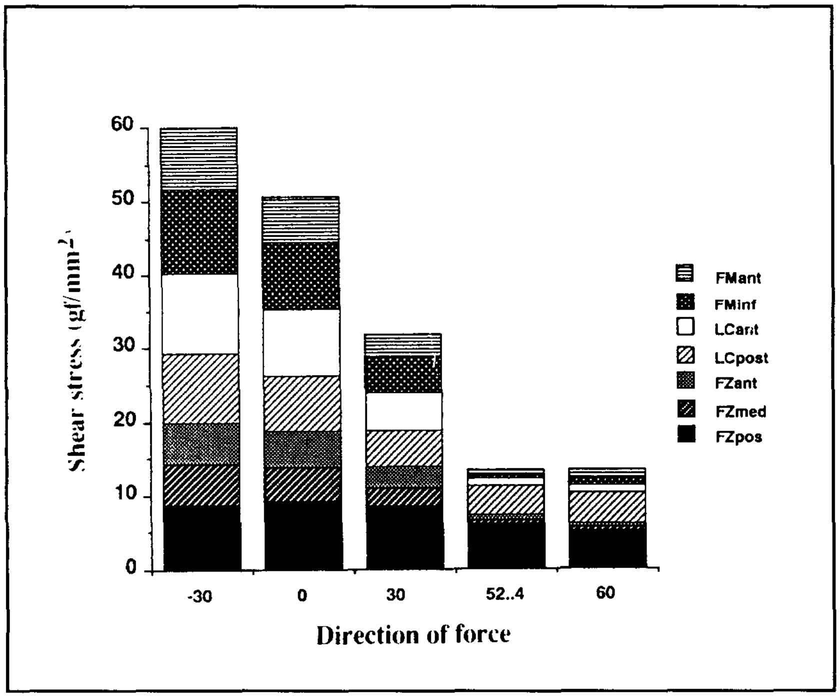

Figure 5

Figure 4
Mean principal stresses in the anatomic areas resisted upward displacement of the complex.

Figure 5
Total amount of shear stresses in the anatomic areas resisting upward displacement of the complex. Shear stress in each area was accumulated for each force application: FM–frontomaxillary suture; LC–lamina cribrosa; and FZ–frontozygomatic suture.

and stress in the periodontium and bony structures for both orthodontic and orthopedic treatments.[19-26] Among these variables, the direction of force may be of great importance in determining the nature of displacement of the nasomaxillary complex produced by orthopedic headgear forces, as in the case of orthodontic tooth movement.[19-21] In a preliminary report, the influences of force direction on sutural responses were indicated[27] and further study was indicated. The present study was thus designed to elucidate, by means of finite element analysis, the nature of sutural responses to headgear forces applied in varying directions.

In this study, normal stresses gradually approached a certain level of uniform compressive stress (-2.5 gf/mm^2) in association with gradual decreases in shear stress, as the force direction passed more closely to the CRe of the nasomaxillary complex.[18,28,29] If the nasomaxillary complex presents pure displacement or translation in the posterior or superior directions, normal stresses at the sutural interfaces should exhibit almost uniform compressive stresses with slight shear stresses, as observed in tooth movement. More uniform stress distribution with less shear stress produced by 52.4° superiorly directed force may indicate almost translatory displacement without substantial counterclockwise rotation of the complex, as was demonstrated in previous studies for tooth displacements and stresses in the periodontium.[20-21] With these considerations, it is indicated that directing the line of headgear force closer to the CRe produces more optimal sutural modification for controlling maxillary growth.

These findings strongly suggest that different headgear forces may produce different morphologic results of the nasomaxillary complex during headgear therapy.[3-8] A preliminary study, using cephalometric analysis, was conducted to examine changes of the nasomaxillary complex during headgear therapy. Changes in size and position of the maxillary complex during orthopedic therapy with cervical or high-pull headgear were compared with normal growth changes in the control group. An interesting finding was that high-pull headgear produced more substantial change in the measurement items relevant to downward growth, whereas cervical pull headgear mainly restricted forward growth of the maxillary complex.[30] These morphologic changes revealed in a clinical aspect would be due to the differences in sutural responses to various forces applied in downward and upward directions. Sutural response, the stresses in the sutural interfaces in particular, is a key determinant of therapeutic change of the craniofacial complex by headgear.[31-33]

Based on the present finding, histologic verification is anticipated to integrate analytic and biologic findings at the sutural interfaces. Since the model used in this study is too complicated to integrate both quantities, a simplified model, comprising a single suture with two bones, will be more useful for understanding the interactions between biomechanical components and tissue reactions.

Conclusions

The present study was conducted to investigate the nature of stress distributions in the sutures produced by orthopedic headgear forces applied in different directions. Finite element analysis was employed, using a three-dimensional model of the craniofacial complex that consisted of 2918 nodes and 1776 solid elements. The model also included 18 sutural systems in the complex. Mean principal and shear stresses were evaluated at six anatomic areas resisting posterior and superior displacements of the complex. The following results were obtained.

1. When 30° inferior, parallel, and 30° superior forces were applied, considerable variation in normal stresses at the sutural interfaces was observed in association with substantial shear stresses.
2. In loading with forces in 52.4° and 60° superior directions, compressive stresses were similarly generated in most anatomic areas and both the normal and shear stresses reduced and exhibited a convergence to a certain level.
3. As the force direction approached that of the CRe, mean principal stresses approached a uniform level of compressive stress.

Stresses in the nasomaxillary sutures are varied by the direction of headgear force, and the force applied in the direction closest to that of the CRe may produce the most effective sutural modification for controlling maxillary growth.

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Table 2
Morphologic changes of the nasomaxillary complex produced by cervical and high pull headgears

Measurement items	Cervical pull n=8	High pull n=8
Horizontal relation		
SNA angle	-0.43 + 0.28**	-0.25 + 0.09**
Ptm-ANS/Pal. pl	-0.37 + 0.33**	-0.28 + 0.40*
S-Ptm/FH	-0.25 + 0.18**	-0.12 + 0.19*
Vertical relation		
Pal. pl.-FH	0.34 + 0.23**	-0.09 + 0.32
N-Pal. pl.	0.75 + 0.48**	-0.30 + 0.44*
S-Pal. pl.	-0.30 + 0.35*	-0.23 + 0.39

*Significant change at 5% level of confidence
**Significant change at 1% level of confidence
Note: For each item, the values before and after headgear therapy are standardized to z-scores by use of the corresponding control data. Changes in the z-scores are shown in this table.

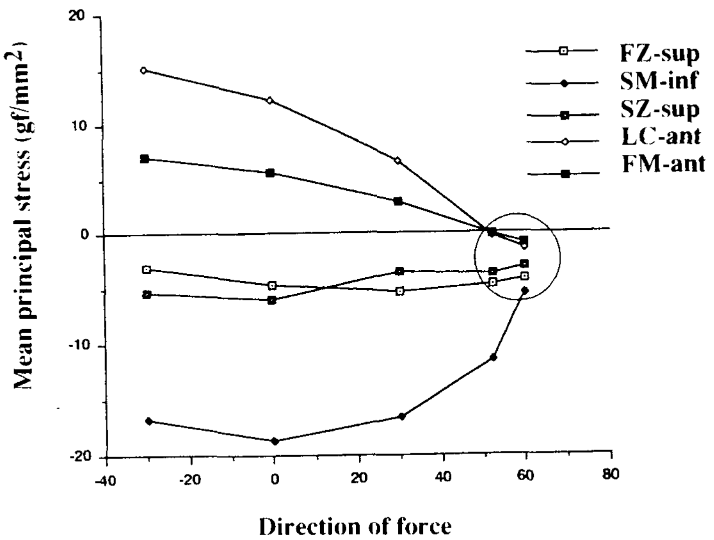

Figure 6

Figure 6
Association between changes in mean principal stresses at five different points and force directions to the functional occlusal plane determined by the maxillary dentition: FM–frontomaxillary suture; SM–sphenomaxillary suture; SZ–sphenozygomatic suture; LC–lamina cribrosa; and FM–frontomaxillary suture.

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