Biomechanical and clinical changes of the craniofacial complex from orthopedic maxillary protraction

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Treating mandibular prognathism is usually complicated because individualized growth prediction for the maxilla and mandible is difficult. Nevertheless, early treatment with orthopedic appliances has been attempted to control craniofacial growth.[1-7] Orthognathic surgery may be needed for some patients with severe skeletal Class III discrepancies. Because the prevalence of Class III malocclusion characterized by maxillary hypoplasia is relatively high, control of maxillary growth is important. Accordingly, a variety of appliances have been designed to reposition the maxilla anteriorly.[8-10]

In order to evaluate the effect of maxillary protraction on maxillofacial growth, experimental and cephalometric studies have been conducted.[8,10-18] According to these studies, the direction of protraction forces is an important factor in determining patterns of repositioning, and sutural modification of the complex is pertinent to its growth change. However, biomechanical stresses or strains in the craniofacial skeleton and its surrounding sutures have not been investigated in detail. These components may be key determinants for bone remodeling. Therefore, it is of clinical significance to understand the biomechanical response of the complex to therapeutic forces when compared to actual morphological changes of the skeleton.

The purpose of the present study was to investigate stress distributions in the craniofacial complex produced by an orthopedic force and, further, to evaluate morphological changes of the skeleton by maxillary protraction therapy.

Finite element analysis and its analytical procedure

Before investigating stress distributions in

Abstract

The present study was designed to investigate biomechanical and clinical changes in the craniofacial complex resulting from orthopedic maxillary protraction by means of finite element and cephalometric analyses, respectively. An analytical model developed from a young human dry skull was used for finite element analysis. Three principal stresses were determined in the complex and its sutures. For evaluating morphological changes of patients, lateral cephalograms taken before and after maxillary protraction therapy were analyzed.

Tensile stresses were produced in the maxillary and zygomatic bones in an anterior direction with corresponding compressive stresses in a perpendicular direction. In the sutural systems, compressive stresses were induced by counter-clockwise rotation of the complex. Cephalometric investigation demonstrated that significant improvement of the maxillo-mandibular relationship was obtained by maxillary protraction, however, maxillary growth and repositioning were not as great when compared to mean growth in the control group.

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Key Words

Maxillary protraction • Finite element method (FEM) • Biomechanics • Stress distribution

the craniofacial complex by use of finite element method (FEM), the analytical procedure is described herein using a simple model of a bone.

Finite element analysis[19] consists of the development of model, data input, execution of analysis and data output.

Since equivalence of the model to a real object is a key to accuracy of the results, construction of the model is the most important step for the FEM. In order to explain the modeling procedure, construction of a model for a long bone is presented.

Contours of five transverse planes of a sheep metacarpus perpendicular to its long axis were precisely drawn on the basis of the study by Churches et al.[20] (Figure 1). Each section was divided into a finite number of elements on the two-dimensional plane, maintaining geometric shapes of real structures (Figure 1). Then, all the transverse sections of the bone were built up in the direction running from the mesial to distal ends. Finally, a three-dimensional finite element model of the bone was developed, consisting of 240 nodes and 128 solid elements.

For data input of the model, nodal coordinates, element description by nodes, material constants of elements, and boundary and force conditions were prepared.

Nodal coordinates were obtained by digitizing the nodes on the two-dimensional sections with the pre-defined coordinates along the long axis. Three-dimensional configuration of the element was given by defining the numbers of nodes located at apexes of the solid elements.

For material constants, both Young's modulus and Poisson's ratio are needed to describe the mechanical behavior of the model in the elastic field. For the model, these values of the compact and cancellous bones were 1.4×10^3 kgf/mm^2 and 0.30, and 8.0×10^2 kgf/mm^2 and 0.30, respectively. Boundary conditions for restraints were established at the mesial and distal diaphyseal points to avoid the rigid body motion, as indicated by solid triangles in Figure 1.

In the FEM, various magnitudes of forces can be applied at any point and in any direction in a three-dimensional space, simulating therapeutic forces. For this model, a 5.5 MPa stress was applied in the dorsal direction at the mid-diaphyseal point.

In order to interpret analyzed results, nodal displacements and stresses were printed out and/or graphically displayed. For this analysis, the computer program ISAP (Integrated Structural Analysis Program, NEC Corp., Tokyo, Japan) was employed. As a result, three principal stresses in the bone are presented as shown in Figure 2. In the dorsal and volar compact

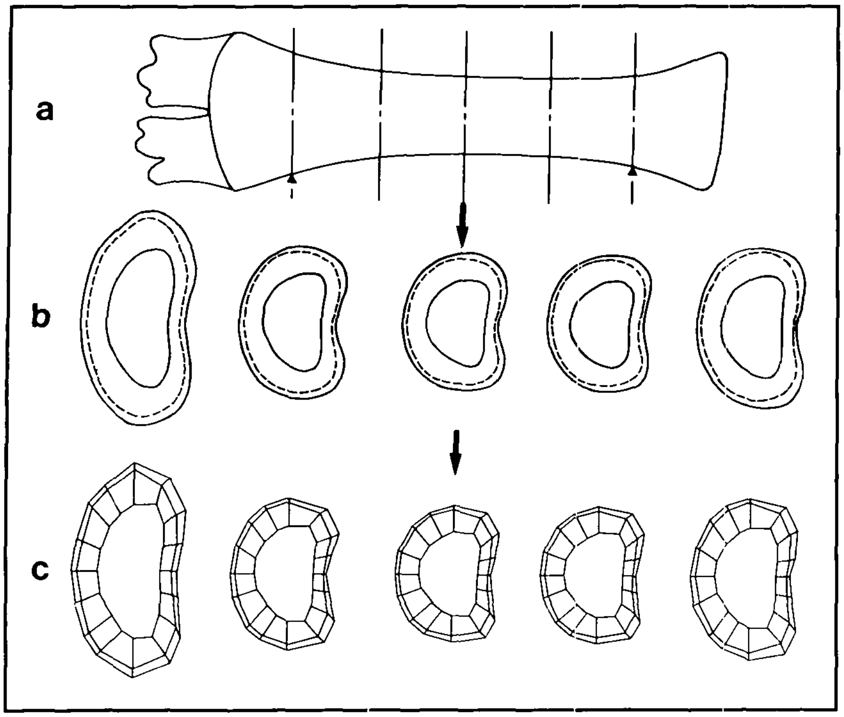


Figure 1

Figure 1
A schematic representation of modeling procedure for a sheep metacarpus.
a: lateral view of the bone. Solid triangles indicate restraints, where no linear and angular displacements were allowed.
b: five transverse sections of the bone.
c: element discretization on the transverse plane.

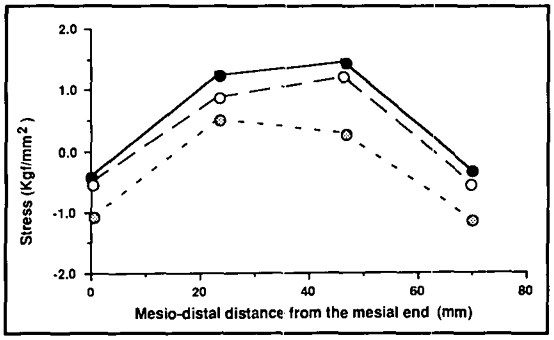


Figure 2a

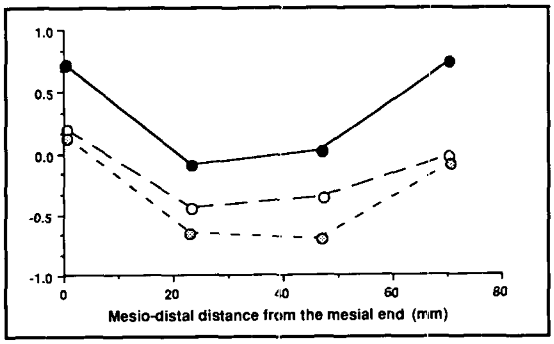


Figure 2b

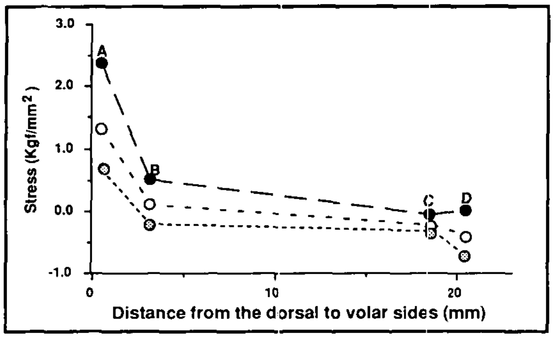


Figure 2c

Figure 2
Stress distributions in the compact and cancellous bones of the sheep metacarpus.
a: three principal stresses in the dorsal compact bone.
b: three principal stresses in the volar compact bone.
c: three principal stresses at the mid-diaphyseal region.
A: dorsal compact bone; B: dorsal cancellous bone; C: volar cancellous bone; D: volar compact bone

bones, tensile and compressive stresses were induced almost uniformly from the mesial to distal ends (Figures 2A, B), indicating bone deformation along the long axis. Stresses gradually decrease from the dorsal compact bone to the volar compact bone (Figure 2C), in concurrence with dimensional changes reported by Churches et al.;[20] thus, stress distributions were directly related to biological bone remodeling. These findings emphasize that finite element analysis for stresses, principal stresses in particular, is useful for understanding biological changes of bony structures.

Materials and methods

Stress distributions in the craniofacial complex were investigated by means of the finite element analysis. Figure 3 shows a three-dimensional model of the craniofacial skeleton from a young human dry skull. Details of the modeling procedure are described in a previous article.[21]

An orthopedic 1.0 Kg force was applied on the first molars of the model in the anterior direction parallel to the occlusal plane. Table 1 shows material constants of three components of the model. The model was restrained at the region around the foramen magnum where no linear and angular displacements were allowed, as indicated by solid triangles in Figure 3. The present analysis was executed using a computer program, FEM 3 (Fujitu Corp., Tokyo, Japan). Three principal stresses were determined in the craniofacial bones and around the sutures.

The effect of maxillary protraction on craniofacial growth was evaluated by means of cephalometric analysis.

Six adolescent patients were chosen as the subjects. All patients underwent maxillary protraction therapy, where a protraction force of 500gf was exerted by elastics to hooks on the maxillary first molars. A lingual arch appliance served as anchorage. Lateral cephalograms, taken before and during or at the end of maxillary protraction therapy, were analyzed by use of a personal computer (PC-9801UX41, NEC Corp., Tokyo, Japan). Details of the subjects are shown in Table 2. For evaluating the effect of the therapy, six measurement items were selected as follows:

1) SNA 2) A-Ptm/Pal. pl.
3) Pal. pl. to SN 4) ANB
5) A-B/Pal. pl. 6) U1 to Pal. pl.

All values were processed to eliminate differences in age and sex among the subjects. Each measurement was standardized using its corresponding mean and standard deviation of Japanese control, and the converted value or z-score was used to analyze standard statistics and to

Table 1
Mechanical properties of different materials of the model for finite element analysis

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

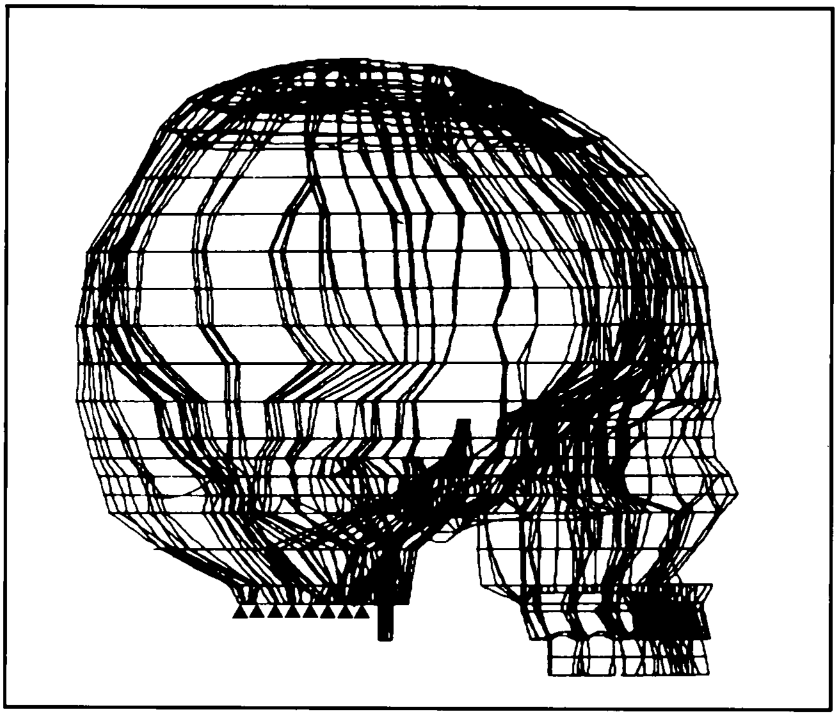
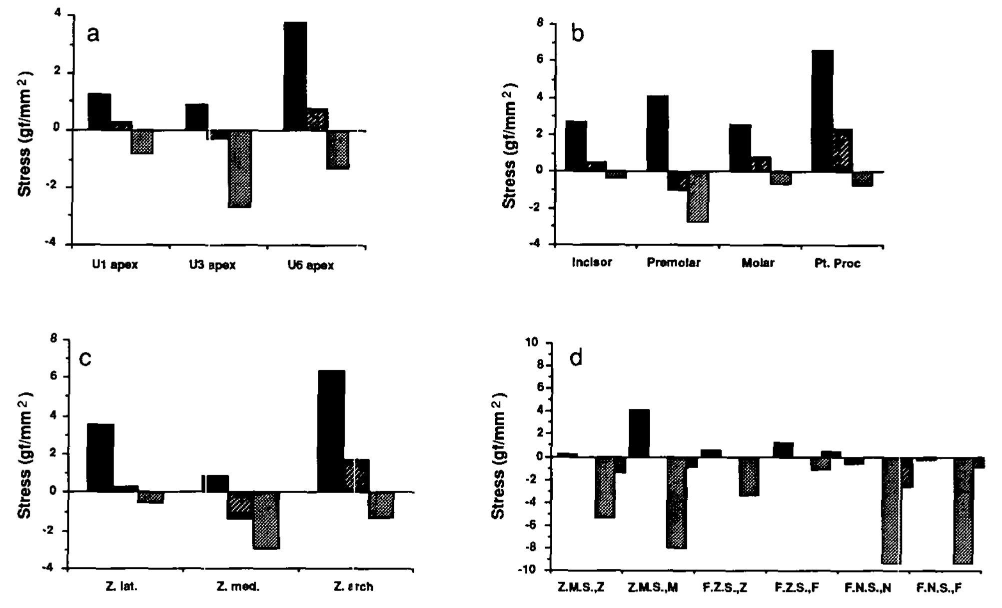


Figure 3

Figure 3
A three-dimensional finite element model of the craniofacial skeleton. Solid triangles indicate restraints of the model.

Figure 4
Stress distributions in the craniofacial bones.
a: three principal stresses in the maxillary alveolar bone at the incisor, canine and molar regions.
b: three principal stresses in the maxillary basal bone at the incisor, premolar and molar regions.
c: three principal stresses on and inside the zygomatic bone and in the zygomatic arch.
d: three principal stresses in the bones facing to the sutures.
Z.M.S.,Z: the zygomatic bone around the zygomaticomaxillary suture.
Z.M.S.,M: the maxillary bone around the zygomaticomaxillary suture.
F.Z.S.,Z: the zygomatic bone around the frontozygomatic suture.
F.Z.S.,F: the frontal bone around the frontozygomatic suture.
F.N.S.,N: the nasal bone around the frontonasal suture.
F.N.S.,F: the frontal bone around the frontonasal suture.

Figure 4



examine mean differences between two treatment stages.

Results

Figure 4 shows three principal stresses in the craniofacial bones, where positive and negative signs indicate tensile and compressive stresses respectively.

In the maxillary alveolar bone (Figure 4A), tensile stresses were observed in a horizontal direction with compressive stresses acting perpendicularly. More specifically, the protraction effect was prominent at the molar region, where tensile stress was approximately 4.0 gf/mm^2. In the canine area, compressive stress was greater than tensile stress.

The maxillary basal bone, including the adjoining pterygoid process, exhibited changes similar to those in the alveolar bone (Figure 4B). Tensile stresses were induced in an anterior direction with corresponding compressive stresses acting vertically. The magnitude of tensile stress was greatest in the pterygoid process and its value was about 7.0 gf/mm^2. These tensile stresses indicate that the maxilla is separated from the pterygoid process at the pterygomaxillary fissure. In the premolar region, relatively large compressive stresses were induced, as was observed in the alveolar bone in the canine area.

On the lateral surface of the zygomatic bone and its arch, large tensile stresses ranging from about 4.0 to 6.0 gf/mm^2 were induced; compressive stresses were observed mainly in the zygomatic bone (Figure 4C).

In the bones around the zygomaticomaxillary, frontozygomatic and frontonasal sutures (Figure 4D), compressive stresses were more prominent. Large compressive stresses of approximately 10 gf/mm^2 were produced perpendicular to the frontonasal sutural plane. In the maxillary bone facing the zygomaticomaxillary suture, relatively large tensile stress was produced according to tensile stresses in the maxillary basal bone. In the frontal and zygomatic bones adjacent to the frontozygomatic suture, stresses were slight compared to those in other sutural systems.

Figure 5 shows cephalometric profilograms of an 8-year 3-month old boy who underwent maxillary protraction. Substantial growth and repositioning of the maxillary complex were observed in the anterior direction, although the point Nasion exhibited only slight anterior displacement. Counterclockwise rotation of the maxillary complex was induced, as noted by change of the palatal plane.

Mean changes of the craniofacial morphology, evaluated by cephalometric analysis, are presented in Figure 6. Maxillary protraction therapy produced a significant improvement in the maxillo-mandibular relationship, as noted by changes of ANB and A-B/Palatal plane. However, anterior repositioning and dimensional change of the maxilla were not large. Counterclockwise rotation of the maxilla was not substantially produced, as indicated by change of Palatal plane to SN. On the other hand, significant tipping of the maxillary incisors in an ante-

Table 2

Summary of subjects used in this study

Subject number	Sex	Age A stage	Age B stage
1	male	8y 3m	10y 4m
2	male	8y 7m	9y 5m
3	male	9y 8m	11y 7m
4	female	9y 2m	11y 2m
5	female	10y 7m	12y 5m
6	female	10y 1m	10y 11m

Treatment stage A: before treatment

Treatment stage B: after the correction of anterior cross-bite by maxillary protraction therapy

Figure 5

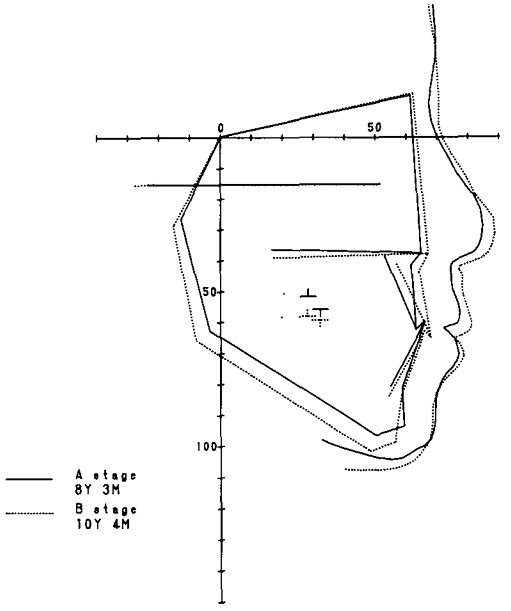


Figure 5
Profilograms of the lateral cephalogram of an 8-year 3-month-old boy before (——) and after (-----) maxillary protraction therapy.

rior direction was recognized as the dentoalveolar effect of maxillary protraction.

Discussion

Since stress or strain in living tissues is thought to be a key factor in biological change,[22-25] it is important to elucidate the stress or strain to understand its relationship to bone remodeling. In orthodontics, various techniques have been employed to measure these biomechanical factors.[26-31] However, it is not always possible with these methods to quantify stress or strain in an internal area of living structures. It is difficult to apply strain gauge techniques[26,30] to the craniofacial skeleton without causing tissue damage. Furthermore, photoelastic[27,28] and holographic techniques[29,31] have a limitation when measuring the biomechanical components induced within the structure.

Therefore, a technique applicable to biomechanical investigation for stress or strain within biological tissues is needed. The finite element method as described in the preceding section, is applicable to the biomechanical study of strains and stresses generated in the internal structures. The results of this study showed that stress distributions in the bone were associated with bone remodeling. Various other studies have reported the relationship between stresses analyzed by the FEM and biological changes of bony structures.[32-35] Thus, the FEM provides the availability and/or the possibility for various biomechanical investigations in orthodontics.

With respect to the effects of maxillary protraction therapy on the craniofacial skeleton, clinical,[8-10] experimental[11-15] and biomechanical studies[16-18] have been performed. These studies have reported that 1) maxillary protraction force produced an anterior repositioning of the maxillary complex in human beings[8,10] and primates;[11-14] 2) various displacement patterns of the craniofacial complex in the anterior direction were produced by varying directions and application points of orthopedic forces;[16-18] and 3) sutural modifications were related to an anterior repositioning of the maxillary complex.[15] The present study demonstrated that 1) maxillary bone and its surrounding bones underwent tensile stresses in the anterior direction, whereas compressive stresses were induced perpendicularly; 2) some sutural systems, such as the zygomaticomaxillary and frontonasal sutures, experienced relatively large compressive stresses acting perpendicularly to their sutural planes; 3) the maxillo-mandibular relationship improved significantly; and 4) substantial — but not significant — maxillary growth and repositioning occurred. These findings are similar to the previous results, with a few exceptions.

In this study, stress distributions produced only by an anteriorly directed force applied to the maxillary first molars were investigated. Large compressive stresses were found in the bones around the maxillofacial sutures in addition to tensile stresses in the maxillary bone. These biomechanical changes in the sutures were understood to be caused by counterclockwise rotation and upward displacement of the complex. Therefore, orthopedic maxillary pro-

Figure 6

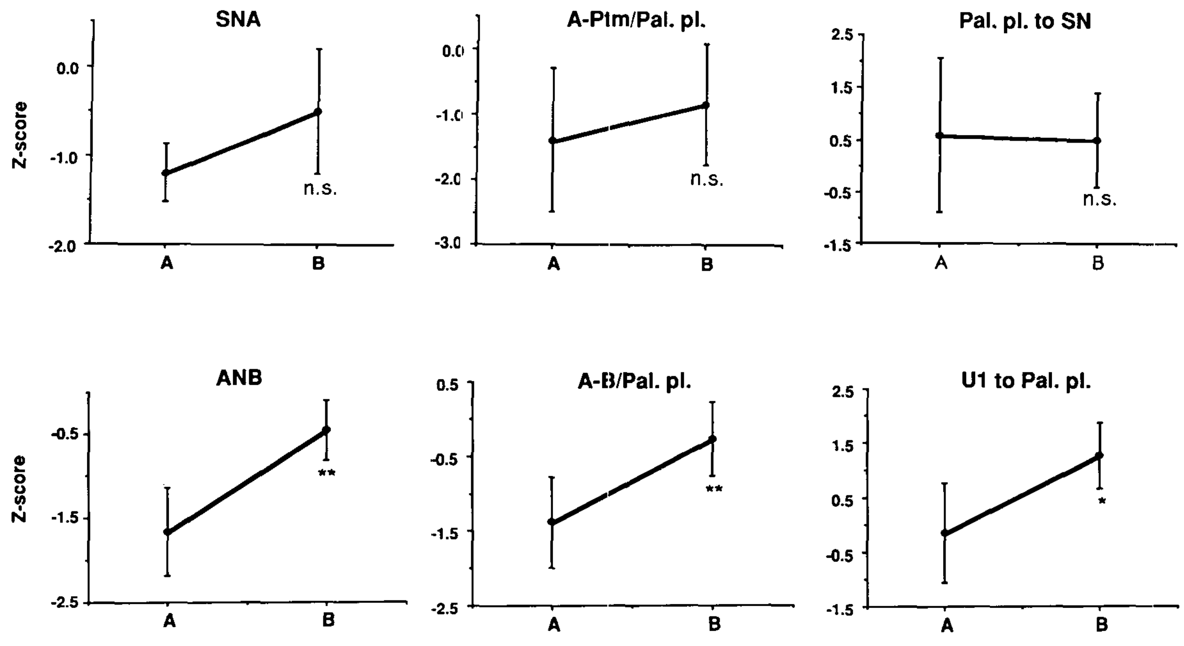


Figure 6
Mean changes of craniofacial morphology with differences in two means at treatment stages A and B, described in Table 2.

n.s.: not significant
***: significant at 5% level of confidence**
****: significant at 1% level of confidence**

traction forces applied in more downward directions and/or at more anteriorly located teeth may eliminate concomitant rotation of the skeleton and produce more efficient sutural modifications for subsequent maxillary growth and repositioning. These considerations will be effective in terms of normal maxillary growth direction.[36]

With respect to morphological changes of the skeleton, dimensional change and anterior displacement of the maxilla were not significant. The duration of maxillary protraction therapy in this study was short and maxillary protraction therapy should normally be continued even after the correction of an anterior cross-bite to achieve significant maxillary growth and repositioning.

In future studies, long-term analysis of craniofacial morphology could be integrated with biomechanical investigation of stresses in the complex from maxillary protraction forces applied at different points and in different directions. These approaches will be useful for elucidating the most effective maxillary protraction therapy for Class III patients.

Conclusions

Biomechanical and morphological changes from maxillary protraction force were investigated by means of finite element and cephalometric analyses. A three-dimensional finite element model of a human dry skull was used and three principal stresses were determined in the craniofacial bones. Further, lateral cephalograms of six adolescent patients with Class III malocclusion, who underwent maxillary protraction therapy, were analyzed.

The following results were obtained.

1. The maxillary complex exhibited tensile stresses in the anterior direction with corresponding compressive stresses in the vertical direction.
2. In the sutural systems, compressive stresses were mainly induced, and were produced by counter-clockwise rotation of the complex.

3. Maxillary protraction therapy produced a significant improvement of maxillo-mandibular relationship. However, maxillary growth and anterior repositioning of the maxilla were not significant compared with mean growth in the control group.

Maxillary protraction force produces anterior repositioning and subsequent growth of the maxillary complex in biomechanical and morphological aspects. The direction and application point of the force are important for inducing more efficient maxillary growth and displacement in the anterior direction.

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