Original Article

# A holographic study of variations in bone deformations resulting from different headgear forces in a macerated human skull

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Headgear appliances are widely used in clinical orthodontic practice. In addition to orthodontic purposes, which include extraoral anchorage and distal molar movement, headgear is frequently employed to produce orthopedic effects, which mainly comprise restriction or redirection of maxillary growth.[1] It is assumed that the maxillary movement necessary for the orthopedic manipulation can be controlled in the same manner as that of a single tooth if forces and moments are correctly managed in relation to the center of resistance of the jaw.[1,2] Extensive theoretical considerations of the mechanics and geometry of extraoral traction and the expected reactive movements of the maxillary complex have been described.[2,3] Although convincing evidence is lacking, these studies are often used when the appliance is prescribed in clinical practice.

Cephalometric studies[4-6] and animal experiments[7,8] have shown that the relationship between the direction and magnitude of headgear traction and the resulting skeletal growth changes is very complex and poorly understood. For the purpose of better understanding this phenomenon, a conceptual discrimination between primary and secondary skeletal reactions to applied forces has been suggested.[9] According to

**Abstract**

The effects of headgear on maxillary displacement and the resulting growth modifications are not completely understood, especially regarding the complex relationships between initial and secondary skeletal reactions on one hand and the influence of the direction and magnitude of the applied force on the other. The aim of the present investigation was to study, by means of holographic interferometry, the initial bone displacement occurring in response to headgear traction applied at different force magnitudes and in different directions. Orthopedic forces of 560 grams and orthodontic forces of 354 grams were simulated on a macerated human skull. The forces came from from high-, straight-, and low-pull headgear traction directed above, through, and below the center of resistance of the maxillary first permanent molars. Immediate skeletal changes were recorded by laser holography. Initial displacements of the maxilla and zygomatic arch in both horizontal and vertical planes were evaluated on frontal and lateral holograms. In most cases, both force magnitudes caused substantial displacements in both planes, albeit to different extents. Complex bending, and rotational, translational, and relative displacements were observed. The direction of displacement did not strictly coincide with that of the applied force. The results of this study indicate that both orthodontic and orthopedic headgear traction may lead to complex initial three-dimensional skeletal displacement in directions not always corresponding with the direction of the applied force.

**Key Words**

Headgear • Orthopedic effects • Skeletal displacement • Macerated skull • Holography

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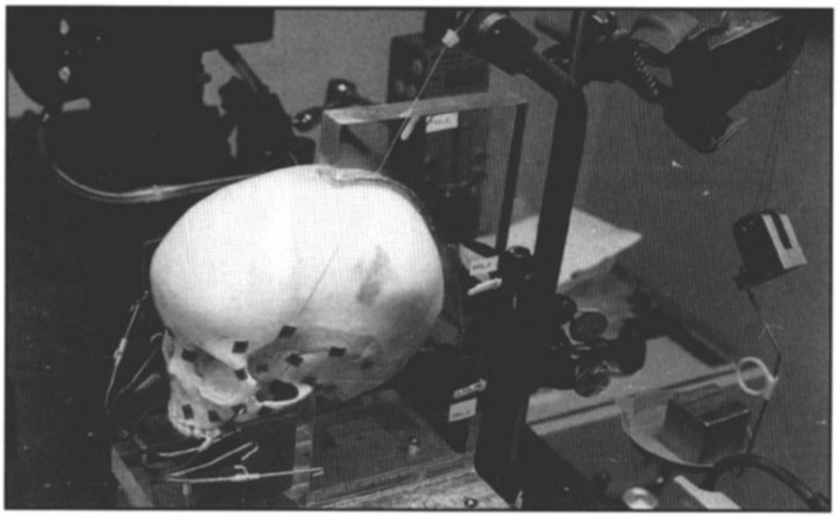

Figure 1

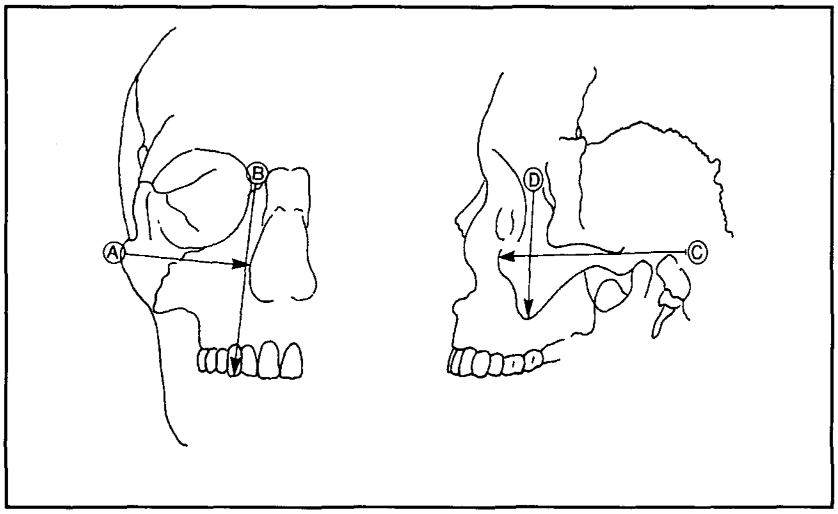


Figure 2

**Figure 1**
**Experimental setup.**

**Figure 2**
**Reference lines A, B, C and D used to evaluate the fringe patterns on the maxilla, zygoma, and zygomatic arch.**

this, primary reactions are initial three-dimensional displacements occurring in the bones immediately after force application, and secondary reactions consist of skeletal tissue remodeling, which is undoubtedly influenced by inherent facial growth potential. In vitro studies have pointed to the complexity of the primary reactions[9-12] and raised new questions regarding the mechanical and geometrical aspects of the effects of headgear traction.

The aim of the present investigation was to compare, by means of holographic interferometry, the extent and direction of the initial skeletal displacement occurring in the maxillary complex of a macerated human skull in response to headgear traction applied at different magnitudes and in different directions. The effects of an orthodontic and an orthopedic force magnitude, as well as those of various traction directions that might be employed in clinical practice,[1,2] were evaluated.

## Materials and methods

Orthodontic molar bands carrying headgear tubes were cemented on the maxillary first permanent molars of a macerated human skull (dental age approximately 6 years). The skull was immobilized in a rigid Plexiglas frame mounted on a vibration-isolated holographic optical bench. A retail-quality headgear was modified and inserted into the tubes to simulate headgear traction as described below.

The extraoral bow of the headgear was adjusted to lie parallel to the occlusal plane, and its hooks were placed at the level of the center of resistance (CR) of the first permanent molars, which was assumed to be approximately 3 mm occlusally to the furcation of the molar roots.[13] These hooks served for the application of traction directed through the CR of the molars. Four additional steel wires were soldered to the extraoral bow, two on each side. Two wires were angulated superiorly and two inferiorly to the occlusal plane, at 40° and 10° respectively. Each of the wires carried two hooks that divided them into a short and long extraoral bow and could be used to apply traction above, below, before, or behind the CR (Figure 1).

Traction was transmitted to the hooks by means of a thin brass wire attached to a weight carrier dish via a wheel that could be adjusted to simulate high-, straight-, and low-pull traction. Orthopedic or orthodontic force magnitudes were produced by placing dish weights of 560 grams (5.6 N) or 345 grams (3.45 N), respectively, on the carrier. The assumption was that the estimated border between orthopedic and orthodontic forces lies at 500 grams.[14] The lines of force tested were determined by the position of the selected hook to which the brass wire was attached and by one of the three height levels available for the pull (Figure 1). By varying the attachment of the brass wire to the hooks on the outer bows of the headgear and alternating the height of the adjustable wheel, the following lines of force relative to the CR were effected:

- low-pull, applied below and before the CR (LP b/b)
- low-pull, applied above and behind the CR (LP a/b)
- straight-pull, applied through the CR (SP)
- high-pull, applied below and behind the CR (HP b/b)
- high-pull, applied above and before the CR (HP a/b).

Skeletal displacement occurring in response to the traction was recorded by means of double



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exposure holography using a He-Ne laser with the wave length of $\lambda$=632.8 nm. This method and its application in biomedical research have been previously described and extensively discussed.[10,15,16] Briefly, at the first light exposure a photosensitive holographic plate is illuminated by two laser beams. One, the reference beam, is aimed directly at the plate and the other, the object beam, is reflected from the surface of the unloaded object. The second exposure is made when the object is under mechanical load. A macroscopically visible fringe pattern is created on the plate by the interference of the beams reflected from the deformed and undeformed surfaces. This fringe pattern reflects the amount and quality of the displacement occurring on the surface of the object.

Frontal and lateral holograms were produced for each traction direction described above and standard black and white photographs were made of the holograms for the subsequent evaluation. In precursor trials control holograms were obtained on different days under identical experimental conditions and were used to test reproducibility of the displacements. Additional controls confirmed that no tension was present in the skull in the absence of a mechanical stimulation and that no motion of the complete skull or the Plexiglas frame took place under loading.

The fringe patterns recorded on the photographs were evaluated by means of the zero-order fringe counting technique as previously described.[16] Templates, two for the frontal views and two for the lateral, were prepared using clear foils with a millimeter grid. On these templates, skull outlines were drawn so the templates and photographs could be accurately superimposed. Each of the templates contained a Cartesian coordinate system and an arbitrarily chosen reference line drawn for the evaluation of displacement occurring in maxilla, zygomatic bone, and zygomatic arch. On the templates for the frontal holograms, reference lines A and B were drawn for the evaluation in the horizontal and vertical planes respectively (Figure 2). On the templates for the lateral holograms these lines were C and D for the horizontal and vertical planes respectively (Figure 2). On superimposition of a template with the respective photograph the points of bisection of the reference line with the dark fringes on the skull were translated into the coordinate system. The x-axis was used to measure the distance in mm between the fringes bisecting the reference line. The y-axis was used to express the magnitude of displacement in wave lengths ($\lambda$) of the light used as the distance between two adjacent fringes corresponds to a displacement of $\lambda/2$ along that distance.[15] The points obtained in the coordinate system were subsequently connected to construct the displacement curves.

## Results

The holograms obtained during the application of LP b/b traction at both orthopedic and orthodontic force magnitudes are shown as examples in Figure 3A-D. It is apparent from these holograms that a substantial displacement occurred in the entire skull under the application of either force magnitude. Higher frequency of the fringes visible on the holograms obtained under the orthopedic force reveals the greater extent of displacement under this condition compared with the orthodontic force. Continuous spread of the fringe pattern over the facial bones reflects a concerted interdependent deformation of these bones while the interruption of the fringes across the calvarial sutures indicates an independent displacement of the individual bones joined by these sutures. A concerted displacement of the facial bones was also observed on the holograms obtained under all other traction applications (holograms not shown). Figure 4A-B depicts the amount and direction of the displacement that occurred along reference lines A - D in the maxillary body, maxillary alveolar process, zygoma, and zygomatic arch. In the horizontal plane (Figure 4A, line A) a posterior deformation took place in the zygomatic bone and zygomatic process of the maxilla in relation to the maxillary body. In the vertical plane (Figure 4A, line B) a marked posterior rotation of the maxilla was observed, which is recognizable through the virtually linear course of the displacement curves on the graph and by the nearly parallel course of the horizontal fringes on the alveolar process and maxillary body in Figure 3A-B. Evaluation of the fringe pattern on the lateral holograms obtained under LP b/b traction showed a distinct lateral bending of the zygomatic arch in the horizontal plane in relation to its origin in the temporal bone (Figure 4B, line C) and no changes in the vertical plane along the reference line D (Figure 4B). All displacements observed were more marked when the force was applied at the higher magnitude.

Skeletal displacement caused in the maxillary complex by LP a/b headgear traction is shown in Figure 5A-B. A moderate posteriorly directed displacement took place in the body of the maxilla in the vertical plane (Figure 5A, line B), which



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Figure 3A

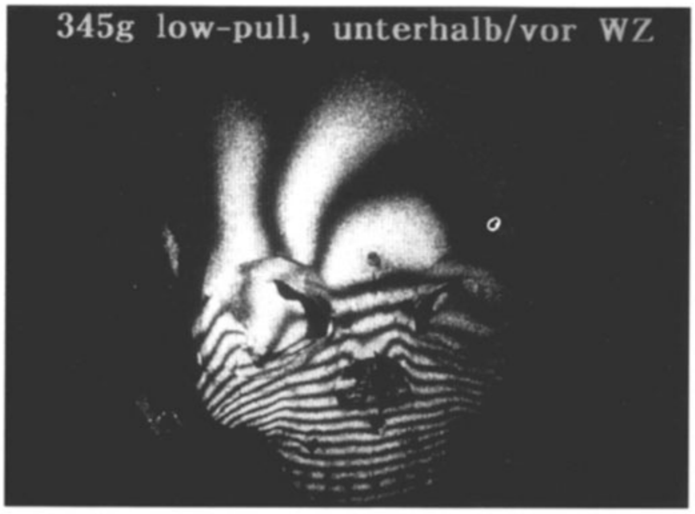


Figure 3B

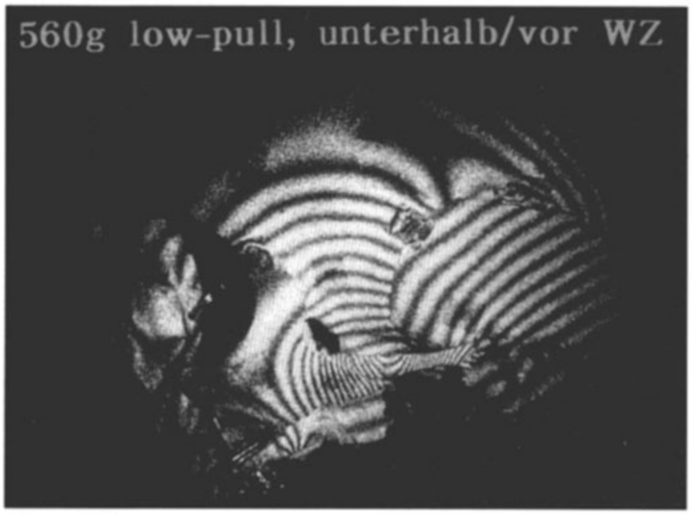


Figure 3C

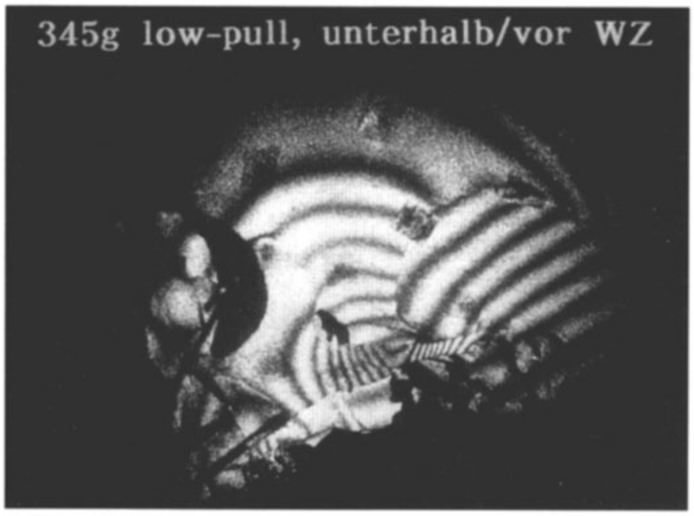


Figure 3D

**Figure 3A-D**
**Frontal and lateral views of holograms obtained when low-pull traction was applied below and before (LP b/b) the center of resistance of the molars.**
**A: Orthopedic force, frontal view;**
**B: Orthodontic force, frontal view;**
**C: Orthopedic force, lateral view;**
**D: Orthodontic force, lateral view.**

in the alveolar process developed into a rotation as indicated by the almost straight course of the distal section of the displacement curves. In the horizontal plane (Figure 5A, line A) this traction brought about a posteriorly directed deformation of the maxillary zygomatic process and a minor anterior rotation of the zygomatic bone, which is expressed by the positive values on the x-axis of the graph. As above, the movements observed were more distinct under the orthopedic load. These displacements were accompanied by a lateral bending of the zygomatic arch (Figure 5B, line C) and a mild transverse compression in the region of the zygomatic bones in relation to the temporal (line C) and frontal (line D) bones as indicated by the negative values on the x-axis. While a measurable displacement occurred along line D under the orthodontic force, no fringes were observed across this reference line under the orthopedic load. This can be interpreted either as a lack of deformation in the frontal process of the zygomatic bone or as an inward translation of the zygomatic bone in relation to the frontal bone. The absence of fringes may indicate such a translation as the interference field might be localized "indefinitely remote" beyond the plane of the object surface.[15]

Evaluation of the fringe pattern formed on the maxillary complex under the SP traction evinced a posteriorly directed deformation of the maxillary zygomatic process and an anterior rotation of the zygomatic bone in the horizontal plane (Figure 6A, line A), the latter shown by the positive values on the x-axis. As no fringes crossed the vertical reference line (Figure 6B, line B) it appears that either a posterior translation of the maxillary body and alveolar process or no movement of these parts took place. These coincided with a lateral bending of the zygomatic arch in the horizontal plane (Figure 6B, line C) accompanied by a slight transverse expansion in the region of the zygomatic bones in relation to the



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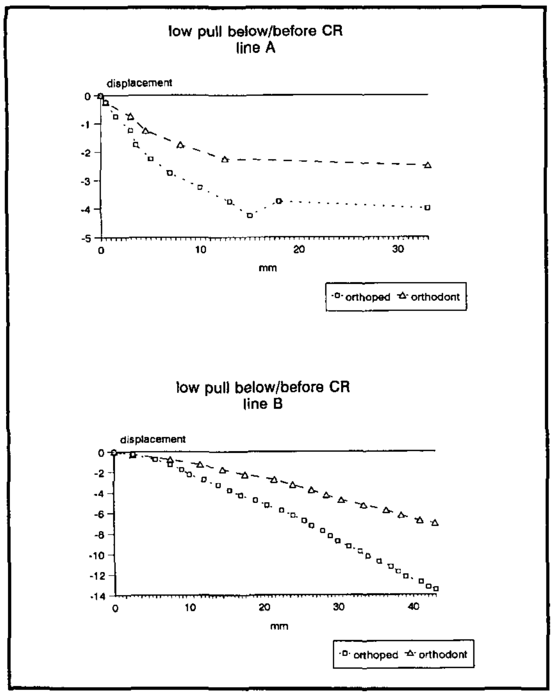


**Figure 4A**

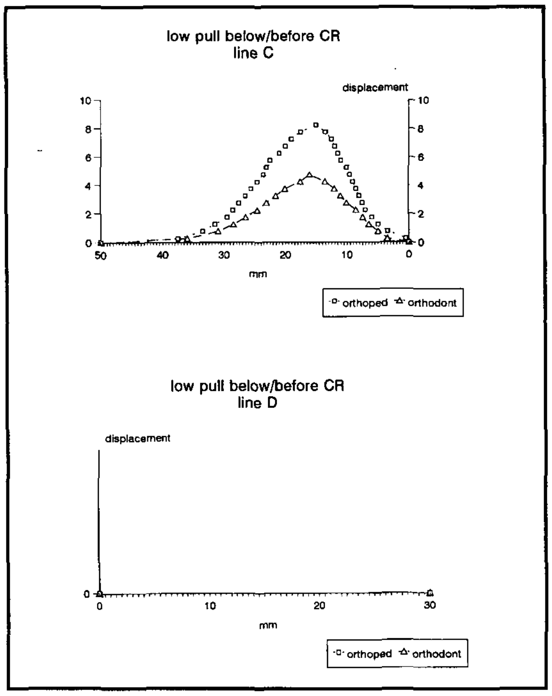


**Figure 4B**

**Figure 4A**
**Displacement curves derived from frontal holograms under orthopedic and orthodontic low-pull traction applied below and before (LP b/b) the center of resistance of molars. The course of horizontal reference line A on the skull from zygoma toward nasal aperture is represented in mm on the x-axis from left to right; the course of vertical reference line B from frontal bone toward canine is represented in mm on the x-axis from left to right. The y-axis shows amount of displacement in wave lengths (λ=632.8 nm). Positive y-values indicate displacement toward the observer's eye, negative ones away from it.**

**Figure 4B**
**Displacement curves derived from lateral holograms under orthopedic and orthodontic low-pull traction applied below and before (LP b/b) the center of resistance of the molars. The course of horizontal line C on the skull from the temporal bone toward zygoma is represented in mm on the x-axis from right to left; course of vertical line D from frontal bone toward zygoma is represented in mm on x-axis from left to right. The y-axis shows amount of displacement in wave lengths (λ=632.8 nm). Positive y-values indicate displacement toward the observer's eye, negative ones away from it.**

temporal and frontal bones (Figure 6B, lines C and D). Under this traction direction, a more marked displacement also occurred under the orthopedic force.

When HP b/b traction was applied, posteriorly directed deformation of the maxillary body and rotation of the alveolar process in the vertical plane were observed, the latter evinced by the straight run of the distal section of the displacement curves (Figure 7A, line B). A complex deformation of the maxilla was detected in the horizontal plane (Figure 7A, line A) where a posterior deformation was visible in the zygomatic bone, zygomatic process, and the region near the nasal aperture while the part between them seemed to project anteriorly. No anterior rotation of the zygomatic bone was apparent (Figure 7A, line A). On the lateral hologram a laterally directed bending of the zygomatic arch and a distinct transverse expansion in the region of the zygomatic bones (Figure 7B, lines C and D) could be identified. Again, the displacements were more apparent when the orthopedic force was applied.

Under the HP a/b traction a minor deformation in the horizontal (Figure 8A, line A) and the strongest deformation in the vertical (Figure 8A, line B) plane were recognized. On the lateral hologram a substantial transverse expansion in the region of the zygomatic bones in relation to the temporal (Figure 8B, line C) and frontal (Figure 8B, line D) bones was observed. In contrast to all other traction directions, no lateral bending of the zygomatic arch was apparent under this condition. All displacements were more pronounced when the orthopedic force was used.

## Discussion

In this study, holographic interferometry was applied to evaluate initial skeletal displacement occurring in a skull under mechanical stimulation. This method combines the advantages of classical optical interferometry and those of holography and allows the measurement of displacement of relatively large surfaces at the level of light wave length.[15] In several earlier investigations, researchers[9,10,16,17] have proved the practicability, validity, and advantages of holographic interferometry when it is applied in orthodontic research. Skeletal displacement was evaluated in the present work using a zero-order fringe interpretation technique as previously described.[16] This technique, which has been extensively discussed elsewhere,[15] was chosen because it has several important advantages, including precision, the ability to discriminate between various types of displacement, simplicity of the optical setup, and convenience of using photographs for evaluation.

While the age of the skull used in this study—6 years—was fairly close to the age of an orthodontic patient, its composition differed from a head in vivo. Lack of strong interdigitation at the sutures and the loss of fibrous connective tissue produced by maceration may lead to more pronounced bone displacement in a macerated skull



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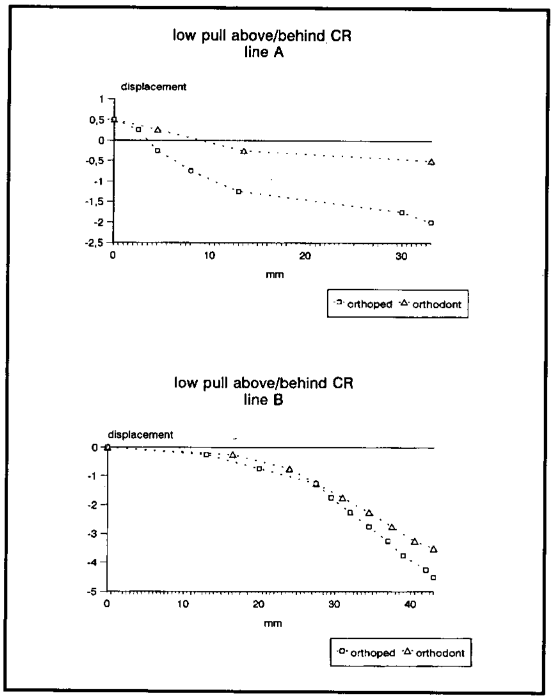


Figure 5A

**Figure 5B**
**Displacement curves derived from frontal holograms under orthopedic and orthodontic low-pull traction applied above and behind (LP a/b) center of resistance of molars. Course of horizontal reference line A on skull from zygoma toward nasal aperture is represented in mm on the x-axis from left to right; course of vertical reference line B from frontal bone toward canine is represented in mm on the x-axis from left to right. The y-axis shows amount of displacement in wave lengths (λ=632.8 nm). Positive y-values indicate displacement toward observer's eye, negative ones away from it.**

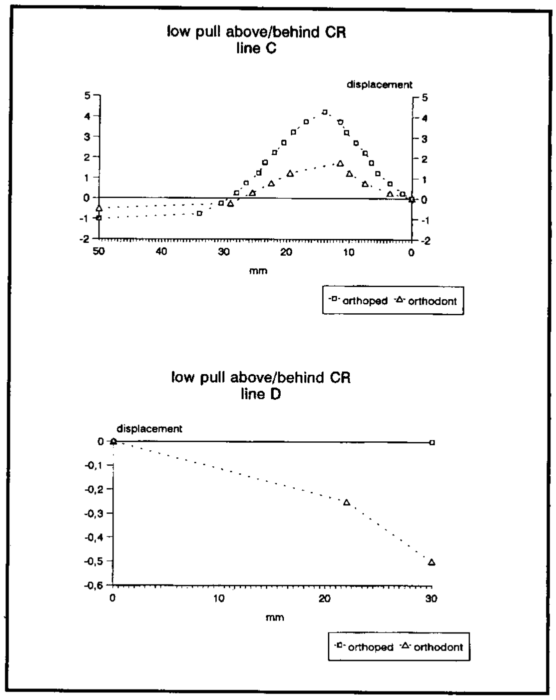


Figure 5B

**Figure 5B**
**Displacement curves derived from lateral holograms under orthopedic and orthodontic low-pull traction applied above and behind (LP a/b) center of resistance of molars. Course of horizontal line C on skull from temporal bone toward zygoma is represented in mm on the x-axis from right to left; course of vertical line D from frontal bone toward zygoma is represented in mm on the x-axis from left to right. The y-axis shows amount of displacement in wave lengths (λ=632.8 nm). Positive y-values indicate displacement toward observer's eye, negative ones away from it.**

than in a head in vivo.[18] However, as the modulus of elasticity of bone is several orders of magnitude higher than that of the remaining connective tissues,[19] and skeletal reaction therefore probably represents the major component of a displacement in vivo,[10] the use of a macerated skull in the present study seemed justified as an approximation of the situation in vivo. Furthermore, a macerated skull had to be used because a wet specimen would require substantially longer exposure times during holographic procedures and could change in shape through evaporation.[20] In any case, the possibility that the macerated skull might inadequately represent a human skull in vivo is not critical, as the present study is primarily concerned with complex effects of commonly used orthodontic force systems on the skull and the different skeletal reactions evoked, and does not attempt to quantitatively evaluate how any given headgear would act on a patient.

The use of a single skull served the purpose of the present study, i.e., to compare the effects of two force magnitudes applied in different directions under otherwise identical experimental conditions. The use of several skulls was rejected in order to avoid the additional variable caused by individual skull morphology, which might obscure subtle qualitative and quantitative differences in displacement.[9,21] Satisfactory precision, accuracy, and reproducibility of the experimental arrangement employed in the present investigation were confirmed in the precursor trials. Reproducibility of displacement of macerated bone was extensively tested by Dermaut et al.,[13] who calculated an error probability of 6%, which is in accord with our observation, albeit a subjective one.

In this study the center of resistance of the maxillary first molar as determined by Dermaut et al.[13] was used as the reference point for directing and describing the line of force. Putative centers of resistance of each individual facial bone and of the entire nasomaxillary complex probably exist and are presumably located within the bones themselves. As such centers have not yet been experimentally localized, no reference is made to them in the present study. However, the angulations of the attachment hooks on the outer bow of the headgear as they were chosen in the present study, allowed force application excentric not only in relation to the CR of the molars but also to the putative centers of resistance of the nasomaxillary complex, assuming that they are located within the maxilla or zygomatic bones. Furthermore, the action of the headgear may be perceived in relation to any facial bone, because the capacity for individual movement of bones at their sutures is clearly present. Therefore, as far as the above centers of resistance are concerned, no strict distinction should be made between the molar and the maxillary complex when discussing the results of the present investigation.



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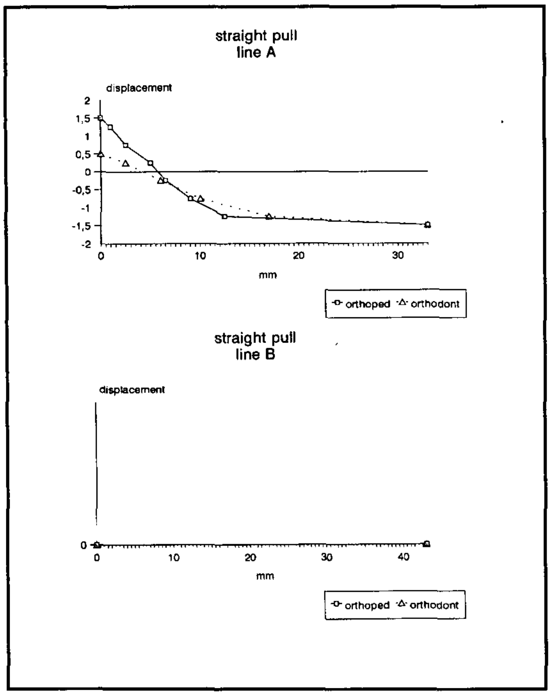


**Figure 6A**

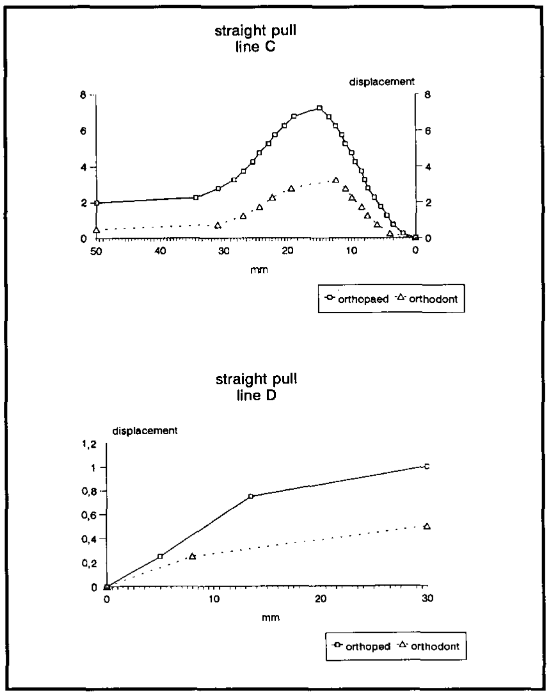


**Figure 6B**

**Figure 6A**
**Displacement curves derived from frontal holograms under orthopedic and orthodontic straight-pull traction (SP) applied through center of resistance of molars. Course of horizontal reference line A on skull from zygoma toward nasal aperture is represented in mm on the x-axis from left to right; course of vertical reference line B from frontal bone toward canine is represented in mm on the x-axis from left to right. The y-axis shows amount of displacement in wave lengths (λ=632.8 nm). Positive y-values indicate displacement toward the observer's eye, negative ones away from it.**

**Figure 6B**
**Displacement curves derived from lateral holograms under orthopedic and orthodontic straight-pull traction (SP) applied through the center of resistance of molars. Course of horizontal line C on skull from temporal bone toward zygoma is represented in mm on the x-axis from right to left; course of vertical line D from frontal bone toward zygoma is represented in mm on the x-axis from left to right. The y-axis shows amount of displacement in wave lengths (λ=632.8 nm). Positive y-values indicate displacement toward the observer's eye, negative ones away from it.**

Under the conditions of this study, the application of both orthopedic and orthodontic forces effected measurable, in some cases substantial, displacement in the entire skull; this was especially true in the maxillary complex. This finding is in accord with the results of another study in which even lower forces, starting above 0.5 N on each side, caused detectable displacement in a macerated skull.[11] In agreement with the observation made by Kragt et al.,[12] who described the transition from independent displacement of individual facial bones to a concerted displacement at force magnitudes above 2.0 N per side, the displacements observed in the present study were concerted at both force levels tested. Although the implications of concerted displacement remain unclear, it seems that substantially lower forces may lead to considerable deformation of facial bones than the forces above 500 grams that conventionally are defined as orthopedic.[14] Should such a displacement be associated with recognizable orthopedic changes of the skeletal structures in vivo, i.e., changes in growth pattern, it would appear that they may be brought about by forces below the magnitudes traditionally regarded as orthopedic.

The displacements in the maxillary complex observed under the conditions of the present investigation turned out to be very complex. Essentially, the direction of the displacements did not coincide with the direction of the traction applied. Bending, rotations, translations, and relative deformations of various parts of the maxillary complex were observed. This variety and the deviation from the traction direction are probably based on the complexity of the architecture of the skull and the varying thickness and size of the bones involved. Some of the observations made in this study confirm previously described findings. Kragt et al.,[10] for instance, demonstrated that an anterior rotation of the zygomatic bone occurred under application of low-pull headgear traction. Posterior rotation of the maxilla in the sagittal plane, which in the present investigation was evinced under all conditions except for the straight-pull traction, is in agreement with previously described observations.[10-12] The absence of fringes crossing reference line B on holograms produced under the straight-pull traction indicates that no posterior maxillary rotation took place in the sagittal plane and that the maxillary body and alveolar process were probably translated posteriorly. The results of the present study suggest that variations in force direction in relation to the CR of the first molars do not influence the direction of maxillary rotation, although they may result in different amounts of displacement. Displacement was more pronounced when the low-pull traction directed below and before and high-pull traction directed above and before the CR were applied. The higher extent of displacement under these traction directions is probably associated with larger shear stress in the sutures of the craniofacial complex, which has been shown for low-pull traction in the study by



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**Figure 7A**
**Displacement curves derived from frontal holograms under orthopedic and orthodontic high-pull traction applied below and behind (HP b/b) center of resistance of molars. Course of horizontal reference line A on skull from zygoma toward nasal aperture is represented in mm on the x-axis from left to right; course of vertical reference line B from frontal bone toward canine is represented in mm on the x-axis from left to right. The y-axis shows amount of displacement in wave lengths (λ=632.8 nm). Positive y-values indicate displacement toward observer's eye, negative ones away from it.**

**Figure 7B**
**Displacement curves derived from lateral holograms under the orthopedic and orthodontic high-pull traction applied below and behind (HP b/b) center of resistance of molars. Course of horizontal line C on skull from temporal bone toward zygoma is represented in mm on x-axis from right to left; course of vertical line D from frontal bone toward zygoma is represented in mm on the x-axis from left to right. The y-axis shows amount of displacement in wave lengths (λ=632.8 nm). Positive y-values indicate displacement toward observer's eye, negative ones away from it.**

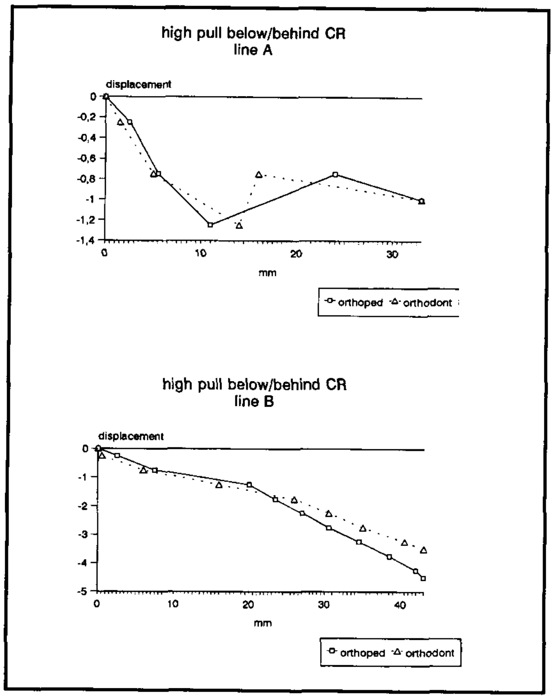


Figure 7A

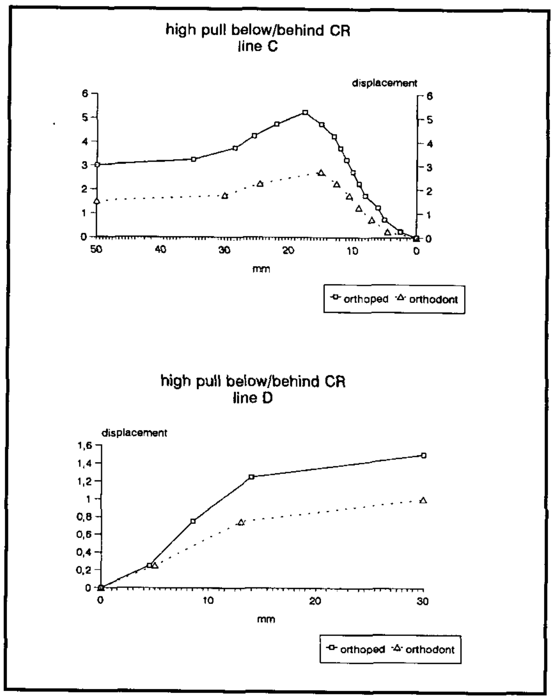


Figure 7B

Tanne et al.[22] This also may explain the more apparent orthopedic effects of low-pull headgear as indicated by cephalometric studies.[23,24] Surprisingly, the number of fringes across the vertical reference line (Figure 8A, line B) in the case of high-pull force applied above and before the CR (HP a/b) was the highest observed under the conditions of the present study. A possible explanation of this finding is that a compression of the circummaxillary sutures occurred under this direction of force based on the anatomical relation of the maxilla to the base of the skull, and that the resistance of the base of the skull led to increased stress within the body of the maxilla and alveolar process, which was expressed in high number of fringes. The significance of the differential displacements that occurred in the zygomatic complex in the transverse and horizontal planes when the direction of traction was varied remains unclear. Whether the expansion observed in the zygomatic complex under the straight- and high-pull traction results in orthopedic widening of the face needs to be verified cephalometrically. This is difficult because the frontal cephalograms that might readily lend themselves to such verification are not routinely used in orthodontic practice.

Traditional analysis of the geometry of headgear effects is based on assumptions about the rigidity of the appliance.[25] However, as pointed out by Marcotte,[26] bending of the headgear bow in any one of the three planes of space probably occurs, relocating the line of force and creating couples at the headgear tube. An experimental verification of the occurrence of such bending and the coinciding couples and moments was recently published.[27] It seems, for instance, that no linear relationship exists in the mesiodistal direction between the distally directed force and the moment based on bending of the outer bow under load.[27] These additional factors have most certainly contributed to the complexity of skeletal deformations observed in the present study. If the above eventualities[26,27] are included, the following additional aspects of the headgear action must be considered. The moments developed by the force will be determined by the force magnitude and the perpendicular distance from the line of force to the CR when the outer bow is loaded. A three-dimensional force system will develop at the CR acting on the molars and the skull as the force is directed excentrically to the CR in all three planes of space. Skeletal deformations observed in the present study were evaluated only in the lateral and frontal planes. The above considerations imply that additional deformations most probably occurred in the third dimension, evaluation of which was precluded by the present experimental setup.

The displacements in the structures chosen for evaluation were accompanied by several other coinciding deformations in the entire skull, as can be seen on the holograms shown in Figure 3A-D. In addition, these displacements represent deformation that occurred in relation to the beginning of the arbitrarily chosen reference lines.



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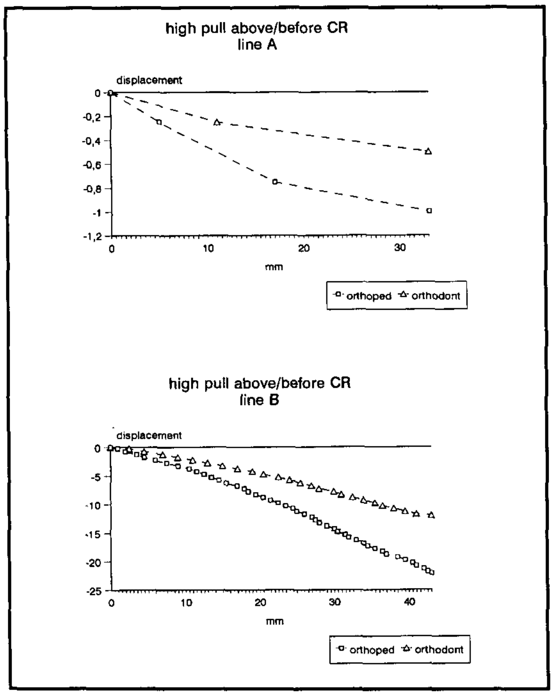


Figure 8A

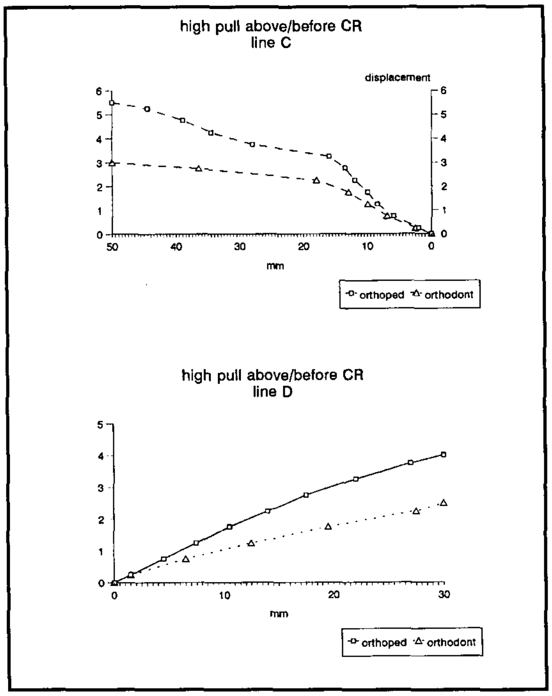


Figure 8B

**Figure 8A**
**Displacement curves derived from frontal holograms under orthopedic and orthodontic high-pull traction applied above and before (HP a/b) center of resistance of molars. Course of horizontal reference line A on skull from zygoma toward nasal aperture is represented in mm on the x-axis from left to right; course of vertical reference line B from frontal bone toward canine is represented in mm on the x-axis from left to right. The y-axis shows amount of displacement in wave lengths (λ=632.8 nm). Positive y-values indicate displacement toward observer's eye, negative ones away from it.**

**Figure 8B**
**Displacement curves derived from lateral holograms under orthopedic and orthodontic high-pull traction applied above and before (HP a/b) center of resistance of molars. Course of horizontal line C on skull from temporal bone toward zygoma is represented in mm on the x-axis from right to left; course of vertical line D from frontal bone toward zygoma is represented in mm on the x-axis from left to right. The y-axis shows amount of displacement in wave lengths (λ=632.8 nm). Positive y-values indicate displacement toward observer's eye, negative ones away from it.**

The lateral bending of the zygomatic arch, for example, was evaluated in relation to its emergence in the temporal bone while any potential relative or absolute displacement of the latter was not considered. This circumstance, as well as the high number of fringes visible on the entire skull, imply that the overall displacements might have been even more complex. If applicable to in vivo events, such complexity suggests that displacements in vivo are likely to be even more intricate and less predictable than if they were consistent with the simplistic concept of the relationship between the direction of the force prescribed and the direction of skeletal displacement and subsequent growth modification obtained,[2,3] which is often used in clinical practice. A cephalometric evaluation of 200 treated patients,[6] for instance, has challenged the view that direction of headgear traction may predictably influence the direction of facial growth.

The displacements observed in the present study represent initial skeletal reactions to mechanical load. Presumably, these displacements contribute to a large extent to the actual orthopedic effects of headgear traction, which probably also depend on the inherent growth pattern of the individual concerned. Whether and how the postulated relationship of these two factors may be instrumental in producing orthopedic changes should be elucidated by future work. A better description and more precise control of the force systems involved are essential for understanding of this complex phenomenon.

## Conclusion

The results of the present study indicate that marked skeletal displacement occurs in the maxillary complex under forces below the magnitude traditionally regarded as orthopedic. Both orthodontic and orthopedic force magnitudes transmitted by headgear result in complex, differential three-dimensional displacement of facial bones. The results obtained under the conditions of this investigation indicate that the direction of this displacement may not be predictably influenced by varying the direction of the applied force in relation to the center of resistance of the first molars.

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