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Hypothetical Evaluation of Stress and Displacement of the Mandible with Chin Cup Therapy Using Various Force Vectors (Finite Element Study)

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الخلاصة

الاهداف:تهدف الدراسة إلى تقيم توزيع الإجهادات والازاحة في الفك السفلي من مختلف اتجاهات القوة التي يولدها جهازchin cup. باستخدام نموذج ثلاثي الأبعاد وطريقة العناصر المحدودة. **المواد وطرائق العمل**: تم إنشاء نموذج ثلاثي الأبعاد للفك السفلي.ومن ثم تطبيق chin cup بقوة ٨٠٠ غرام على الذقيني للفك السفلي. كان اتجاه القوة (١٥، ٢٠، ٢٥، ٣٠، ٣٥، ٤٠، ٩٠) درجة بالنسبة إلى محورا لسيني ، ثم تم قراءة الاستجابات الميكانيكية. **النتائج**: لوحظت أعلى مستويات الإجهاد في منطقة مفصل الفك، وزيادة الاجهادات كلما تم نقل متجه القوة بعيدا عن مفصل الفك. وقد نزح الفك السفلي إلى الأسفل والى الخلف عندما يمر متجه القوة أسفل من أو خلال مفصل الفك (مع الزوايا ١٥، ٢٠، ٢٥). والى الأمام وإلى الأعلى مع مرور ناقلات القوة بعيدا عن المفصل(مع ٣٠، ٣٥، ٤٠، ٩٠). **الاستنتاجات**: متجه القوة هو من العوامل الهامة وبالتالي ينبغي النظر بعناية عند ربط الجهاز.

ABSTRACT

Introduction: Early orthodontic treatment is recommended, since the morphologic pattern of the prognathic face associated with excessive forward mandibular growth is most likely established early in life. The chin cup is the preferred orthopedic appliance for growing children with mandibular prognathism and a normal maxilla. **Aims Of Study:** Evaluation of the stress and displacements in the mandible from various chin cup force vectors, using three-dimensional finite element model. **Materials And Methods:** Three-dimensional model of the mandible was modeled and analyzed. Chin cup with 800 g force was applied on the pogonion of the mandible. The direction of the loading vectors were 150, 200, 250, 300, 350, 400 and 900 relative to x axis, then, the mechanical responses in terms of displacement and Von Mises stresses are evaluated. **Results:** The highest stress levels observed in the condylar, posterior ramus regions and inferior sigmoid notch, and increased as the force vector was transferred away from the condyle. The mandible was displaced in downward and backward direction with the vector passing below and through the condyle (with angles 150, 200 and 250) forward and upward displacement was recorded as the force vector move away from the condyle (within 300, 350, 400 and 900). **Conclusions:** With the limitations of modeling, boundary conditions, and solution assumptions, chin cup applied in various directions produce different force vectors, which induce different stress and displacements. The force vector is an important determinant of the orthopedic effects of the chin cup and therefore should be carefully considered.

Key words: Chin cup, finite element.

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INTRODUCTION

In clinical orthodontics, skeletal Class III malocclusions are considered among the most difficult cases to treat. Subjects with Class III may display maxillary retrusion, mandibular protrusion, or combination of the two.[1] Mandibular prognathism is responsible for about 20% of skeletal class III malocclusions and originates from imbalances in mandibular size, form, and position with respect to the maxilla or the cranial base.[2,3]

Malocclusions are not self-correcting and actually worsen during growth and development, because of excessive forward mandibular growth.[4,5]

Early treatment orthodontic is recommended, since the morphologic pattern of the prognathic face associated with excessive forward mandibular growth is most likely established early in life. The chin cup is the preferred orthopedic appliance for growing children with mandibular prognathism and a normal maxilla.[6] The effects of the chin cup on dentofacial growth have been investigated in both animal experiments and cephalometric analyses.[7]

Meanwhile, bone remodeling is currently considered to be highly related to mechanical stresses induced in bony structures. Since biologic changes of bony structures are produced in stressed areas, biomechanical components such as strains or stresses from orthopedic forces should be investigated with morphologic changes of the mandible. This approach might be important to elucidate the mechanism of remodeling of the mandible and also provide the clinical implications for orthopedic chin cup therapy to orthodontists.[8]

In this study, the finite element method (FEM) was used to evaluate Stress and displacements in the mandible from various chin cup force vectors on the mandible.

MATERIALS AND METHODS

In the FEM procedure with a process called discretization, a mathematical model is built up.[9] Models of complicated structures are made by breaking the structures down into smaller pieces called elements.[10] In this way, complex problem is subdivided into smaller and simpler problems, with infinite freedom of the object becoming finite freedom and it can be solved by using numerical techniques[11,12,13].

The point of application, the magnitude, and the direction of force can easily be varied to simulate the clinical situation.[14]

The FEM requires exact knowledge of the geometry of the mandible under investigation.[15] The computerized 3D solid model of the mandible is formed by using commercially available computer-aided design tools and they necessitate vectorial data of the mandible at several point.[16] Adried human mandible is used to create a 3D FEM model, several points on the surface of the mandible were determined, and their coordinates were stored in the computer. Those nodal coordinates were used to draw external periphery lines (successive and closed boundary curves) to represent the external borders of the mandible. Solid body or model is defined using slicing and loft operation. This solid body is converted to a Standard Text file DWG Text file is imported into the FEM program Autodesk Inventor Professional Computer program version 2012.

After meshing the volume of the mandible, elements and nodes were formed as shown in the Figure (1).

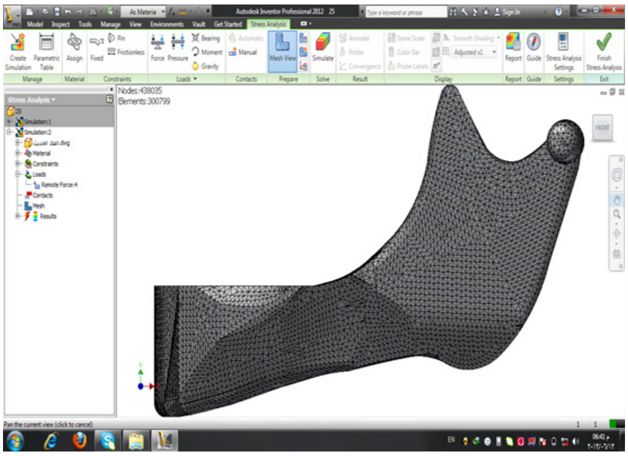

Figure (1): 3D model of Mandibul, after meshing.

Unfortunately, by using this technique, inner material differences cannot be modeled. We assumed the mandible to be homogeneous. In real situations, the movement of the mandible is prevented where the muscles and the ligaments attach to the mandible and condyles however; realistic modeling of soft tissues and temporomandibular Joints is difficult. As a result, an assumption had to be made about the support conditions of the mandible to prevent rigid body translation or rotation of the mandible by restraining or fixing at some nodes, this describes the boundary (support) conditions. In a previous study, the tops of 2 condyles were fixed in space[18]. Fixed support at the top of the condyles is assumed for most FEM models[19,20,21,22].

The precise organic properties of the bone, as in most studies, it is assumed to be isotropic, homogeneous, and linearly elastic.[17] This assumption was also made by previous researchers, and the mechanical constants of the elements were determined by reference to previous studies (young's modulus 9.1 MPa and the poisson's ratio 0.24).[17] In this way, the real anisotropic properties of the mandibular bone are simplified.[19,23] The type of loading was static and valuated as a constant parameter. The loading was applied on the pogonion of the mandible, and the value of the loadings was equal to (7.840 N). The direction of the loading vector was 15, 20, 25, 30, 35, 40 and 90 degree relative to x axis, when the force apply with 25 degree (line of force acting directly through the head of the condyle), 15 and 20 degree (line of force acting below the condyle) 30, 35 and 40 (the force vector pass anterior to condyle), 90 degree is the vertical one. After defining the geometry, elements, loading, and boundary conditions with the SOLVE module, the mathematical analysis was carried out, and the stress and displacement results of every node were produced as shown in Tables (1) through (7).

Table (1): Duncan multiple Analysis Rang Test for Von Mises stress for Infradental location with different chin cup force vectors.

Variables (angles)	Number	Mean	Standard deviation	Duncan test
15	5	0.22520	0.008438	B
20	5	0.20300	0.000707	C
25	5	0.14600	0.003536	E
30	5	0.18180	0.006017	D
35	5	0.23700	0.004690	B
40	5	0.43400	0.026077	A
90	5	0.18600	0.008944	D

Different letters mean there are a significant difference ($P \leq 0.05$) between the angles mean.

Table (2): Duncan multiple Analysis Rang Test for Von Mises stress for Menton location with different chin cup force vectors.

Variables (angles)	Number	Mean	Standard deviation	Duncan test
15	5	0.13320	0.004658	B
20	5	0.11060	0.004159	C
25	5	0.08000	0.004528	D
30	5	0.03940	0.001140	E
35	5	0.00880	0.001304	F
40	5	0.00300	0.001581	F
90	5	0.16400	0.023022	A

Different letters mean there are a significant difference ($P \leq 0.05$) between the angles mean.

Table (3): Duncan multiple Analysis Rang Test for Von Mises stress for Ramus anterior location with different chin cup force vectors.

Variables (angles)	Number	Mean	Standard deviation	Duncan test
15	5	0.10240	0.013183	F
20	5	0.13180	0.005891	EF
25	5	0.15160	0.004159	DE
30	5	0.18340	0.005177	D
35	5	0.23220	0.005263	C
40	5	0.34800	0.019235	B
90	5	0.57000	0.080623	A

Different letters mean there are a significant difference ($P \leq 0.05$) between the angles mean.

Table (4): Duncan multiple Analysis Rang Test for Von Mises stress Gonial location with different chin cup force vectors. for

Variables (angles)	Number	Mean	Standard deviation	Duncan test
15	5	0.01080	0.001924	F
20	5	0.01680	0.001483	E
25	5	0.06480	0.003114	D
30	5	0.07580	0.005630	C
35	5	0.11360	0.003647	B
40	5	0.16540	0.002302	A
90	5	0.11400	0.005477	B

Different letters mean there are a significant difference (P≤ 0.05) between the angles mean.

Table (5): Duncan multiple Analysis Rang Test for Von Mises stress for Ramus posterior location with different chin cup force vectors.

Variables (angles)	Number	Mean	Standard deviation	Duncan test
15	5	0.10080	0.008289	E
20	5	0.07660	0.005505	E
25	5	0.09800	0.008367	E
30	5	0.20000	0.015811	D
35	5	0.31400	0.027928	C
40	5	0.53800	0.040866	B
90	5	0.77200	0.019235	A

Different letters mean there are a significant difference (P≤ 0.05) between the angles mean.

Table (6): Duncan multiple Analysis Rang Test for Von Mises stress for Condylar location with different chin cup force vectors.

Variables (angles)	Number	Mean	Standard deviation	Duncan test
15	5	0.20820	0.005630	D
20	5	0.13020	0.005020	DE
25	5	0.10040	0.005683	E
30	5	0.20300	0.012042	D
35	5	0.30040	0.005683	C
40	5	0.50040	0.005683	B
90	5	1.37400	0.186762	A

Different letters mean there are a significant difference (P≤ 0.05) between the angles mean.

Table (7): Duncan multiple Analysis Rang Test for Von Mises stress for Coronoid location with different chin cup force vectors.

Variables (angles)	Number	Mean	Standard deviation	Duncan test
15	5	0.000	0.000	A
20	5	0.000	0.000	A
25	5	0.000	0.000	A
30	5	0.000	0.000	A
35	5	0.000	0.000	A
40	5	0.000	0.000	A
90	5	0.000	0.000	A

Different letters mean there are a significant difference (P≤ 0.05) between the angles mean.

RESULTS

several points on the mandible at different critical locations were selected. The stress distribution was evaluated according to the stress hypothesis of Von Mises stress in a material equals.

$$\sqrt{(Ơ1\_Ơ2)^2\_\ (Ơ2\_Ơ3)^2\_\ (Ơ3\_Ơ1)}$$

Where Ơ1, Ơ2, and Ơ3 are the principal stresses. The principal stresses are the maximum and minimum normal stresses in a plane, always perpendicular to each other, and oriented in directions for which the shear stresses are zero.[21] For an overview of the stress distribution, color scale with 12 colors served to evaluate quantitatively the stress and displacement distributions in mandible see Figures (2) and (3).

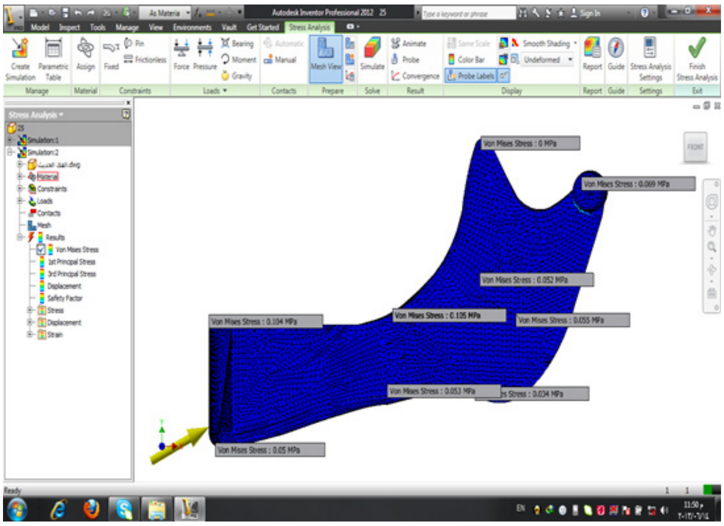

Figure (2): Von Mises stress values for the selected anatomical points.

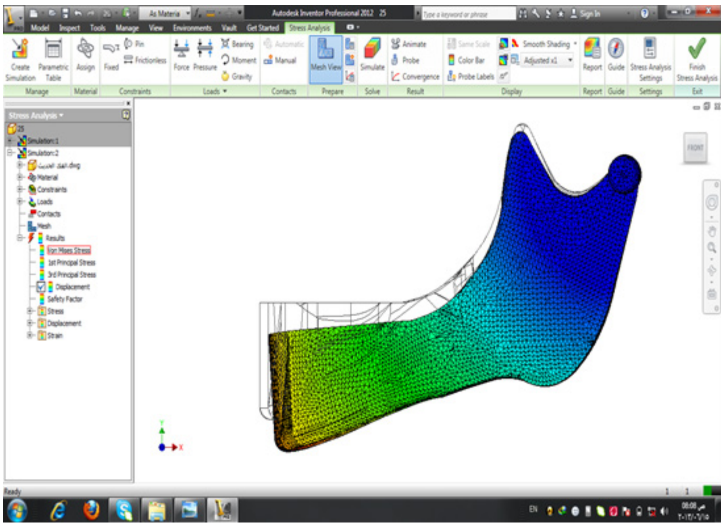

Figure (3): Displacement of the Mandible under chin cup force.

In general, the force vector passing through the condylar head induced little or no stress at all locations tested. The stresses were more prominent in the infradental and retromolar areas and decreased toward the distal part of the mandible, the stress level for this vector was lowest in the coronoid region. The von Mises values were generally higher with the force vector passing anterior to the condyle were particularly high at the posterior ramus and condyle regions.

The force vector passing through and below the condylar head induced inferior displacement (opening rotation) of all locations tested, whereas the force vectors anterior to condyle produced superior displacements (closing rotation) of the mandibular locations almost no displacement was observed condylar region. The displacements were most prominent in the infradental, retromolar and antegonial regions with all angles (15, 20, 25, 30, 35, 40 and 90). The magnitude of displacements was lowest in the condylar vector and highest in the vector passing anterior to the condylar for all anatomic locations.

DISCUSSION

To explore the association between mechanical stress and bone remodeling, biochemical and biomechanical studies have been carried out,[29] biomechanical studies have revealed that principal stress or the relevant strain energy density is a key determinant to remodeling of the alveolar and craniofacial bones incident to functional and orthopedic forces[18,21,28,30]. for long bones, it is also indicated that mechanical strains from functional or dynamic forces play a role in altering the shape of bones.[31]

In this study, we made some assumptions and simplifications to model this complex physical problem For example, the mechanical properties of the materials are nonlinear and complicated, and it might be impossible to include ideal properties. For this reason, some assumptions were accepted to simplify the real situation. The stress-strain relationship of the material was assumed to be linearly elastic, homogeneous, and isotropic. When we considered the results from the uncut hemimandible tests, we concluded that elastic changes occur rather than irreversible deformation. The weaknesses of the model include that, the geometric model of the mandible can change from person to person. This makes the problem even more complex. On the other hand, ˙Işeri et al stated that similar results were obtained by Tanne et al,[33] who used a model with different skull geometry. They showed that, although there were differences in craniofacial structures between subjects, the responses to the same mechanical forces were the same in the FEM.[34,18]

The lowest stress and displacement values is observed when the force vector pass through the condyle this value increase as the force vectors move away from the condyle either in clock or counter clock wise direction. This might be regarded as an expected change, since the force used is the same, the moment induced by this force is significantly increased as the lever arm is lengthened as the force vector moves away from the condylar head from where the mandible in the FEA was fixed

In this study, it found that, the direction of the force vector affect the stress value of each point, this may be due to change in the x and y component for each force angle, since the force amount and point position are the same.

In general the displacements decreased from anterior to posterior part (the anterior part is more away from the fixation point than the posterior part) and almost there is no displacement was observed in inferior sigmoid notch, with zero displacement for condylar (fixation point).

CONCLUSIONS

1. Chin cup applied in various directions produce different force vectors that induce different stress locations and displacements.
2. The force vector passing through the condylar head caused little stress; it induced inferior and posterior displacements of all locations tested, that might be favorable for most Class III patients.

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