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Stresses Induced on Anterior Teeth During Retraction by Two Different Space Closure Mechanics Using Skeletal Anchorage Devices (FEM Study).

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Abstract: Introduction: The stresses resulted from force application during different methods of anterior teeth retraction using skeletal anchorage is not fully informative in the literature regarding the preference retraction method. **Aim:** The purpose of this study was to measure the stresses loaded on the teeth during different orthodontic retraction methods depending on skeletal anchorage system using the finite element method (FEM) for stresses calculation. **Materials and methods:** Geometric models for maxillary buccal segments were created by Cone-beam computed tomography scanning which includes, the first permanent central and lateral incisors and canine. Two 3D finite element models for simulation of two different retraction methods (en-masse retraction method and two- step retraction method) were constructed. These models were then meshed and analysed (Solidworks 2015, Dassault Systèmes, Vélizy-Villacoublay, France). Both retraction methods were simulated by applying the forces using mini-implant as a temporary skeletal anchorage mechanics. The software was used to compare the stresses loaded on the alveolar bone, periodontium, crown, and root during anterior teeth retraction. **Results:** The results have shown that, stresses produced from both anterior teeth retraction methods were non-significant ($p>0.05$). **Conclusion:** Stresses produced from en-masse retraction were concentrated mainly at the area of canine. There was no significant difference between the stresses produced from the two methods of retraction.

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Keywords: Computer simulation, Finite element analysis, Orthodontic stresses, en-masse retraction

1. Introduction:

Many controversies concerning the achievement of maximum anchorage in extraction cases were present. Proffit and Fields[(1)] informed that in order to obtain an absolute anchorage it is better to do separate canine retraction, because this method will allow the stresses loaded on the periodontal ligament area of the anchor tooth to be disintegrated. They informed that closing space in two steps rather than one would take nearly twice as long.

Canine retraction first was also recommended by Roth[(2)]in maximum anchorage extraction cases but did not recommend it for moderate ones.

Skeletal anchorage devices were advantageous in Orthodontic treatment as they facilitated the movement and decreased anchorage loss.

The FEM was first introduced in dental biomechanical field in 1973[(3)] and since then it was used in calculating and analyzing the stress and strain in the teeth and alveolar support structures [(4)].

Many questions arise, where are the areas of maximum force concentration? How do these heavy forces get gradually dissipated? Moreover, is it possible to control maxillary anterior teeth during their retraction in sagittal and vertical plane by changing the vertical levels of force application in the posterior area? Surveying the literature, it was found that this point is not much clarified. Accordingly; the study will be carried out to highlight this point.

2. Material and methods:

The current finite element analysis, designed in this study, simulates a clinical situation; upper anterior segment retraction by en-masse or by two step retraction methods.

A model representing human skull with permanent dentition where a mini-implant as a skeletal anchorage is placed between first molar and second premolar using simulated closing coil spring force action for both retraction methods exerting force of 150 N[(8)].

FEM is recognized as a general procedure for mechanical approximation to all physical problems that can be modeled by differential equation description. Basically, FEM represents a mathematical modeling strategy of the load upon an object. Accordingly, the amount and the area of stress concentration can be calculated.

After Selecting proper analytical model without any discontinuity in the craniofacial anatomy and no gross defect in the model, CT image was performed in a DICom (Digital Imaging Communication in medicine) format using Toshiba (Aquilion 64) multi-slice CT scanner. After that, the CT scan images were exported to Materialise Mimics program (Materialise Interactive Medical Image Control System) (Fig.5) to perform cropping of the CT scan images.

Selecting the desired structures of craniomaxillary complex from the whole skull images was performed by importing the files of CT scan images then selecting the sagittal cuts to crop. Threshold all hard tissue components of the CT images was performed. Finally, editing the masked images by circular eraser and deleting all structures other than the target structures was done.

The cropped files were saved as JPEG extension files by standardizing the cropped images with adjusting the X and Y axis of each image and saving print screen shots of all processed images to gain 30 photos of 5 mm interval.

Designing the main maxillary body

The body of one half of the main maxillary model was constructed by dividing it into two parts, maxilla and orbital floor in one part, zygomatic bone and zygomatic arch in the other part. The body of the first part was constructed by drawing 31 (2D) sketches, drawn on the frontal plane. Every 2D sketch was drawn in a separate plane with 5 mm interval distance between every plane and the other one.

Every 2D sketch was drawn by tracing the imported picture from Materialize Mimics. This step was done by using (Solidworks 2015, Dassault Systèmes, Vélizy-Villacoublay, France)(fig 1).The drawn sketches were joined together with the loft property to create a 3D model of one half of the basic maxillary body and zygoma. Maxillary sinus and nasal cavity were drawn by lofted-cut property of the model.The opposite half was generated by mirror imaging of the first half through the right plane to acquire the final model.

Drawing of permanent teeth was based on the anatomical landmarks of every tooth. Root length, cervical line width, anatomical crown length and outline geometry of every tooth were considered. Drawing the root of every tooth was done by tracing every coronal cut obtained from CBCT images of the selected tooth root. On the top plane, the cervical areas were drawn by drawing the cervical coronal cut of the natural tooth and loft it to the cervical portion of the simulated root.

The occlusal surfaces maxillary teeth were constructed according to anatomical outline of such tooth (Incisal edge for incisors and canine or occlusal surface for premolar and molars)(fig 2,3)

The Orthodontic appliances

Two techniques of anterior segment retraction were considered; En masse retraction and Two steps retraction. Tooth bone retraction method was simulated, which are the Titanium Mini-screw fixed between first molar and second premolar and closing coil spring

Drawing of the screw was performed by drawing of sagittal sketch of the screw according to its anatomical dimension and then revolving was done to the sketch around the midline to form the general outline of the screw. Serrations were drawn by forming helix and spiral curve along the length of the screw. Swept cut was done to the pitch element along the helix curve to form the serration of the screw.

The constructed components were assembled together to form the two model's assemblies. As The technique of model assembly depends on the mating function presented in the assembly mode in solid work program software. The mating function created one or more geometrical relationship between different components. The mates used in this model were coincident and parallel. The mating was accomplished between the teeth and the maxilla as well as the screw with the maxilla.

Homogeneity, isotropy and linearly elastic were considered to all materials in the study. The modulus of elasticity and poison's ratio for the different component materials used in the study are listed in the (table 1).All components were constructed in a way that assured 100% contacts along every interface i.e. that no gaps or interfaces.

The restraint property allows prescription of displacements on vertices, edges, or faces for use with the static analysis. For both retraction methods; all the elements could be used for the specific retraction method. The only restraint applied was a fixture restrain on the back of the maxilla. Load application was done in the two models as the closing coil simulation was applied by 150 N on both sides

Meshing is the process of subdividing the geometric model into small pieces called elements connected at common points called nodes. In this model, high quality solid mesh was used to create 3D parabolic tetrahedral solid elements. (Fig.4)The resultant nodes produced by the solid meshwork were allowed to translate along any of the orthogonal directions unless a restraint was applied.The global average element size was set to 5 mm and the mesh tolerance was set to 1mm.(table.2)

After finishing all manufacture criteria and all meshing parameters, the analysis was run by the FFE plus solver which is an iterative method to solve the equations using approximate techniques where, in each literation, a solution is assumed and the associated errors are evaluated.

Running of the two models were achieved by forming surface to surface bonding, establishing stiffness matrix, preconditioning, establish nodal force balance and then stress calculation. The von Mises stress was calculated at the elements in Mega Pascal (Mpa).Calculation of the average stress value for the elements was considered using the stress, factor of safety, displacement, and strain as results of interest.

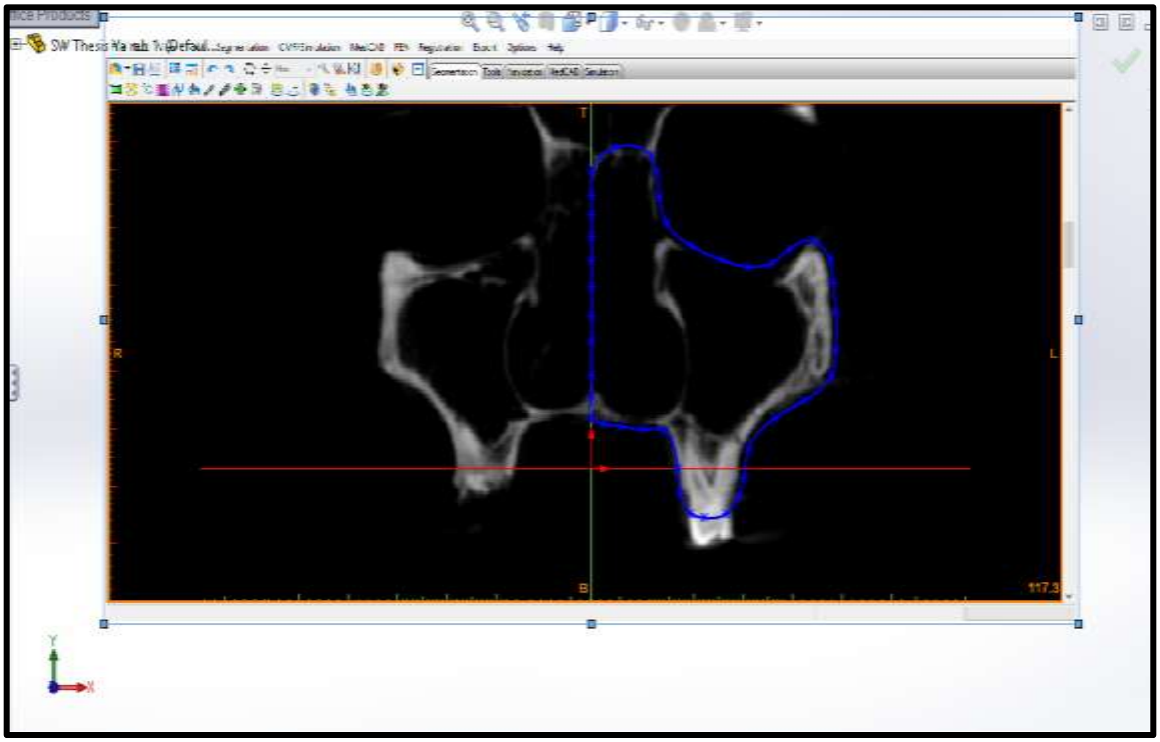

Figure. 1: Tracing the imported images.

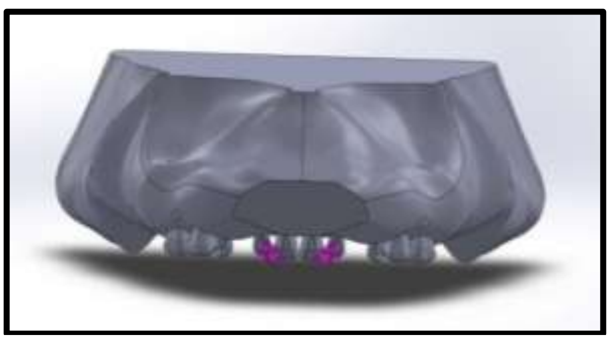

Figure. 2: En-masse retraction.

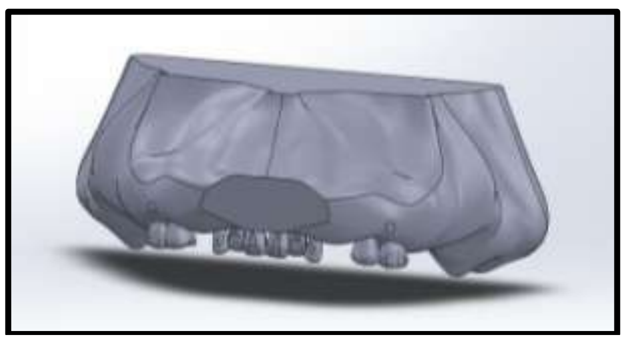

Figure. 3: Two step retraction.

Table (1): Elastic properties of materials used in studies [9-12].

Material name	Modulus of elasticity (Mpa)	Poison's ratio	Mass Density (kg/m3)	Yield Strength (Mpa)
Spongy bone	13700	0.3	1900	170
Teeth	22000	0.3	1020	371.6
Titanium mini screw	117000	0.33	4428.78	750

Figure. 4: Meshing of the model.

Table (2): Meshing properties of each model.

Model no.	**Number of nodes**	**Number of element**
Model A (Canine Retraction)	164232	113838
Model B (En-masse Retraction)	171354	118968
Model C (Incisor Retraction)	174796	121658

3. Results:

Stresses were analyzed at each anterior tooth (crown, apex, alveolar bone and periodontal ligament) as well as at the miniscrew (head, apex and perialveolar bone).

Minimum, maximum, and average values were used for comparing the results in both two-step retraction and en-masse retraction.

In central incisors; root, PDL and alveolar bone, en-masse showed higher stresses than two step retraction, while crown showed higher stresses in two step retraction than en-masse retraction. The highest stress was detected at the distal alveolar bone followed by mesial alveolar bone and finally apical PDL showed the minimal stress.

In lateral incisors; crown, root, PDL and alveolar bone, en-masse showed higher stresses than two step retraction. The highest stress was detected at the distal alveolar bone followed by root and finally apical PDL showed the minimal stress.

In canines; crown, root, PDL and alveolar bone, two step showed higher stresses than en-masse retraction. The highest stress was detected at the crown followed by the distal alveolar bone and finally apical PDL showed the minimal stress.

In head, serrations and perialveolar bone, two steps showed higher stresses than en-masse retraction. The highest stress was detected at the serration followed by the mesial alveolar bone and finally the head showed the minimal stress.

Table (3): Anterior teeth stress values.

	En-masse retraction			Two-step retraction		
Anterior teeth	Central incisors	Lateral incisors	canine	central incisors	lateral incisors	canine
Crown	0.02638	0.143	9.849	0.03169	0.152	27.633
Root	0.17428	0.267	0.572	0.15780	0.150	1.263
Alveolar Bone (Distal)	0.18316	0.557	2.730	0.15205	0.236	8.330
Alveolar Bone (Mesial)	0.13875	0.239	0.679	0.12844	0.176	1.078
Alveolar Bone (Apical)	0.08364	0.119	0.197	0.07228	0.073	0.522
PDL (Apical)	0.00009	0.052	0.014	0.00007	0.026	0.052
PDL (Distal)	0.00038	0.186	0.104	0.00031	0.093	0.374
PDL (Mesial)	0.00039	0.142	0.029	0.00032	0.071	0.103

Table (4): Mini-implant stress values.

Mini-implant						
	En-masse retraction			Two-step retraction		
	Max.	Min.	Avg.	Max.	Min.	Avg.
1) Head	0.003	0.002	0.002	0.009	0.004	0.007
2) Serration	0.111	0.088	0.107	0.306	0.265	0.292
3.a) Alveolar Bone (Distal)	0.122	0.091	0.104	0.279	0.260	0.269
3.b) Alveolar Bone (Mesial)	0.120	0.081	0.102	0.304	0.265	0.289
3.c) Alveolar Bone (Apical)	0.124	0.074	0.105	0.281	0.261	0.270

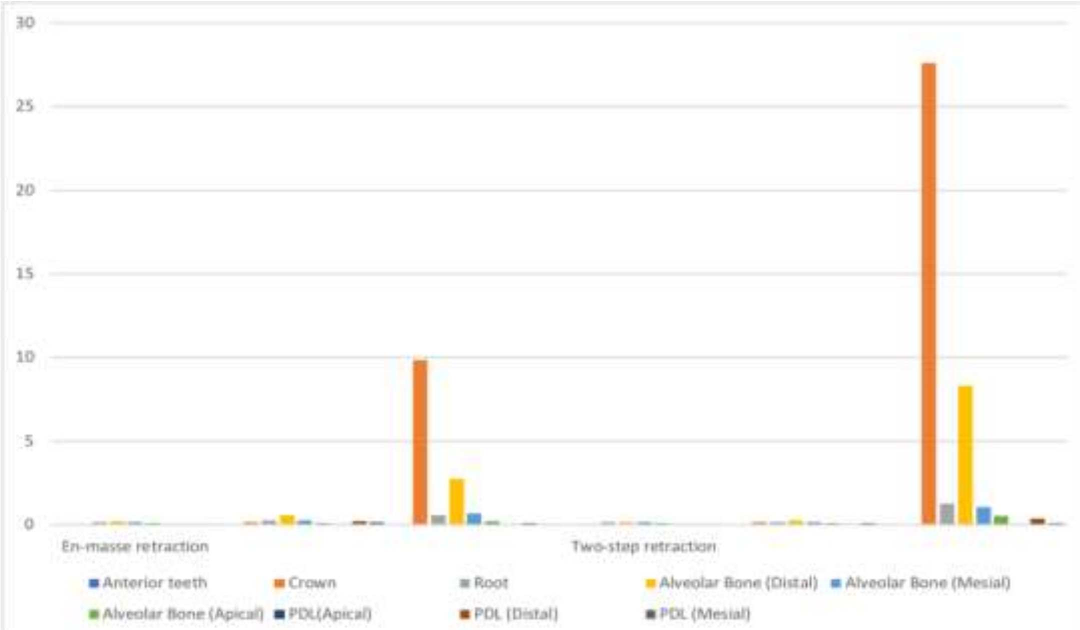

Figure. 5: Central incisor stress values.

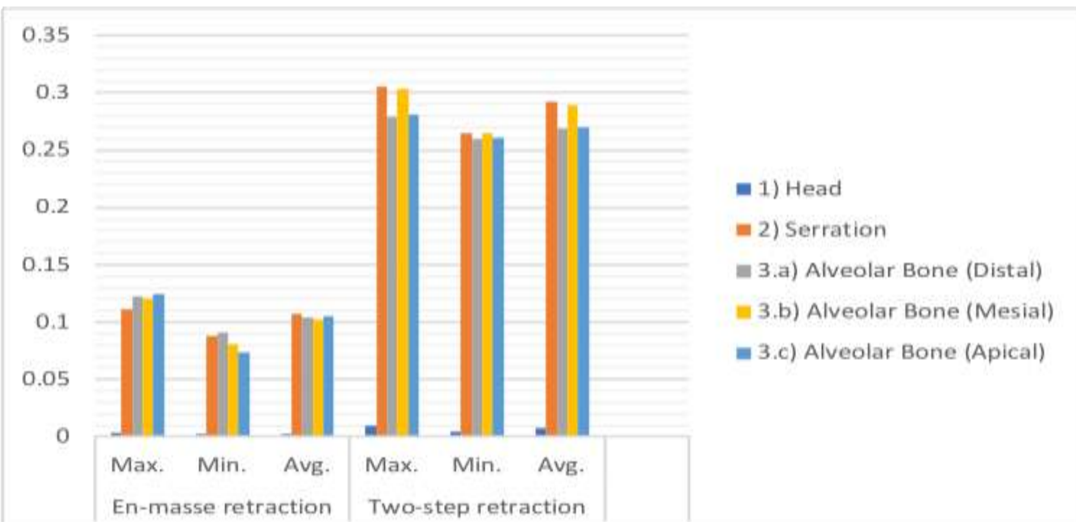

Figure 6: Mini-implant stress values.

Fig. 7: Stresses during two-steps retraction.

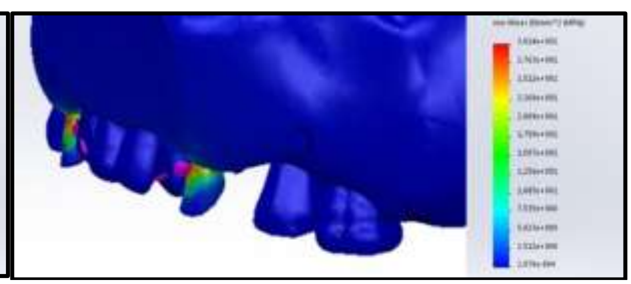

Fig. 8: Stress during En-masse retraction.

4. Discussion:

The base of FEM were the discretization procedures which reduces the problem to one of a finite number of unknowns. These procedures were done by dividing the region of concern into elements and each element was expressed into unknown field variable in terms of assumed approximating functions within each element.

FEA have great disadvantages which must be kept in mind. FEM don't necessarily detect how the stresses are affected by multiple problem variables these variables are the geometrical features, material properties and errors in input data. These produces may be overlooked by the analyst.

The contact problem is considered as the main software obstacle encountered. Any gap presents between any surfaces produce error in meshing procedure and discontinuity problems during the analysis. So, it was necessary to assume that every contact between two bodies must be along its whole surface.

Mating procedures is another method to avoid this problem by collecting the model components by (Coincident and parallel). This method prevents any gap between components. The homogenous, linear elastic and isotropic assumption described for all the materials doesn't apply practically to the bone which shows anisotropic, heterogonous and viscoelastic nature(11,12,13).

Non-living materials follow physical laws under which each material reacts elastically till its yield strength then plastic deformation starts. Otherwise, bone shows a dynamic state of deposition and resorption in reaction to stresses which are below its mechanical yield strength. So, the computer simulation of the two methods can only describe a comparison between the different models but can't guarantee that every model exhibits clinically accepted levels of stresses.

Construction of the model was done through manysteps(14); dividing the continuum into many element was considered the first step. Different element shapes may be present in the same solution region. The number and the type of elements are matters of engineering judgment and the analyst can rely on the experience of others for guidelines.

Nodes were assigned to each element and interpolation function was selected to express the variation of the field variable over the element polynomials. Interpolation functions are easy to integrate and differentiate. Determination of the matrix equations was done by expressing the properties of each elements.

Assembling all the element properties must be performed. The matrix equations were combined to express the behavior of the elements and forming the matrix equations expresses the behavior of the entire system.

The system equations have to be modified and designing the boundary condition of the problem to be ready for solution. Finally, was the assembly process which gives a set of simultaneous equations that are solved to obtain the unknown nodal values of the problem.

Pre-processing step was considered as one of the principle steps. Constructing the model part is constructed, analyzed and divided into several discrete sub regions or elements which is connected at discrete points called nodes. Some of these nodes had fixed displacements, and others had prescribed loads.

In preprocessor stage, the prepared data set was used as input to the finite element code which constructed and solved a linear or nonlinear algebraic equations system. Otherwise, in post-processor display, colored contours is overlaid representing model stress levels which produced full-field picture of photo elastic results.

In linear elastic material, the elastic modulus is defined as the stress value in that direction that obtain a unit strain in the same direction. The modulus of elasticity was introduced by Young and is often called Young's Modulus(15).

Longitudinal direction extension is combined by lateral directions contraction. Poisson's Ratio is defined as the ratio of lateral contraction in the Y-direction divided by the longitudinal strain in the X-direction. Poisson's ratios in all planes are equal(15).

Automatic detection tool was ensured in contact features which was used to find the sets of contact for both touching and non-touching faces within a defined clearance. Selection of the components and bodies were done to let the program find the sets of contact between the target components.

A similar bonded contact was assumed for the ligament-bone contact and tooth-ligament contact. This was followed by model fixtures. Fixtures define fixed restraints. The faces with fixtures are constrained in all directions. One face of the part at least had to be fixed to prevent the failure of the analysis due to the body motion rigidity. The fixtures property in solid works software had the ability to allow zero or non-zero displacements on both vertices and faces as well as frequency and buckling in the dynamic and nonlinear studies.

When applying a force to a face or an edge, the specified value represents the magnitude only. The absolute values were set equal to the force value of the forces applied to each face. The magnitude of load applied in activation stage in retraction mechanics was 150 N(7) bilaterally.

The static load in this study was essential to direct horizontally at the mini-implants to achieve a realistic modeling. Load was directed along axis of the mini-implants to avoid any eccentric force and prevent any dissipation from the screws or retracted teeth.

The curvature-basedmesher in the software was utilized rather than standard mesh. The curvature-based mesher supports the compatibility of the meshing between each touching solid face. Any interference between bodies was checked before meshing.

Debating was present when selecting between von Misses stress and principal stress values in stress calculation stage in the bone. Elastic properties of the bone as it is a brittle material support the researchers who adopted the use of the principal stress and should be described with the maximum and minimum principal stresses.

The stresses in the anterior teeth (crowns and roots), periodontal ligaments, screw (head and serration) as well as the perialveolar bone were analyzed.

The highest stresses were present mostly at the anchorage unit; mini-implant during two-step retraction.

Within the force distribution in en-masse retraction, the highest area of stress concentration was distributed over the whole anterior segment and the stress area merge distally toward the retraction vector. This was in accordance with the studied conducted by Al-Sibaie S, HajeerMY[6].

The central incisor force distribution was mainly higher in en-masse retraction except in the crown, where minimal stresses were clarified because the forces are distributed over the whole anterior segment.

The lateral incisor force distribution was mainly higher in two step retraction, which can be attributed to the fact that force was distributed over 6 teeth in en-masse while in two step it is concentrated over only the canine.The canine force distribution was mainly higher in two step retraction than en-masse retraction.

The mini-implant force distribution was mainly higher in two step retraction, which is attributed to the fact that the forces are generated on the mini-implant as it acts as an anchorage unit while, in the two-step retraction method more stresses are loaded for retraction of canine and the anterior segment.

The PDL present in the pathway of stresses in both models acted as stress absorber to mimic the stress transfer to the surrounding bone. This concept became clear when comparing between stresses applied on the vital structures in both models.

Al-Sibaie S, Hajeer MY[6] stated that en-masse retraction is better than two step retraction in terms of movement rapidity, dentoalveolar changes, loss of anchorage, and aesthetic outcomes due to a bodily retraction (-4.42 mm) was achieved. Also, showed that the two-step retraction was achieved by controlled palatal tipping using anchorage of TPA.

It was reported thatdistribution of stress over the PDL was within the range of optimal stress value for intrusive and lingual root torque movements (Hemanth M), as proposed by Lee[5].

However according to Proffit[14], distribution of stress over the PDL was exceeding the suitable forces for movement of teeth orthodontically with linear properties.

Application of the same force load was applied in non-linear analysis. Stresses were found to be higher in comparison with linear analysis. Moreover, it was above the optimal stress range as proposed by Lee for both lingual root torque and intrusion.

Forces loaded on teeth were acceptable and favorable and the periodontal ligament act as a stress absorber to decrease the stress transfer to the surrounding bone. This concept became clear when comparing between stresses applied in both methods of retraction. Stresses at the central incisor in two step retraction were markedly less than the same in en-masse retraction.

Conclusions:

1. Stresses produced from en-masse retraction were concentrated mainly at the area of canine.
2. There was no significant difference between the stresses produced from the two methods of retraction.

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