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RESEARCH ARTICLE

THE OPTIMAL ATTACHMENT DESIGN AND POSITION DURING ORTHODONTIC TREATMENT WITH REMOVABLE THERMOPLASTIC ALIGNER FOR EXTRUSION OF MAXILLARY CENTRAL INCISOR:FINITE ELEMENT ANALYSIS

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Abstract

Objectives: Finite element analysis (FEA) is a non-invasive virtual model; it has the advantage of being able to forecast the results without direct application to patients.The current study was conducted to simulate various shapes and positions of attachments for the extrusion orthodontic treatment scenarios of maxillary central incisor using the FEA to originate the optimum shape of attachment for each condition and to analyse the best position for attachments by simulating diverse attachment positions for each attachment.

Materials and Methods: This study was conducted to identify the optimal attachment designs (square, round, and triangle) and positions (incisal, middle, and gingival) with RTA during extrusion and intrusion movement of a maxillary central incisor model tooth using FEA. To construct several models and evaluate stress distribution and displacement for comparative analysis, this study used FEA.Specimens preparation was performed as 3D finite geometric models.This study did not employ statistical analysis.

Results: The round-shaped attachment was projected to be the most suitable attachment form for the extrusion of maxillary incisor tooth movement. The lower middle position is optimal during central incisor extrusion.

Conclusion: When the attachments were manufactured in a round shape and placed in the lower middle position a lot of stress was applied to them by the RTA orthodontic device.

Introduction:-

The increased demand for the more aesthetic orthodontic appliance has led to the revolution of invisible appliances such as ceramic brackets, lingual brackets, and removable thermoplastic aligners (RTAs).[1, 2]Clear aligners are desired over others by adults as they exhibit superior aesthetics and give more comfort.[3]RTAs also comprise a broad range of applications in correcting various malocclusions similar to fixed devices and are also termed clear aligners.[2, 4]RTAs are active clear plastic trays fitting snugly onto the teeth, each worn for two weeks on average, and changed sequentially to accomplish the incorporated tooth movements.[5]RTAs being used for mild malocclusion cases from the beginning to treating a vast diversity of cases, from minimal crowding to bicuspid

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extractions, clear aligners have come a long way and continue to progress.[6, 7] However, with the advancement and progression of technology, these RTAs can now be manipulated as a series of removable thermoplastic appliances that are custom-tailored, transparent, and esthetic alternatives to traditional metallic braces for correcting malocclusion.[7] Therefore, computer-aided design computer-aided milling (CAD-CAM) technology was used to make a more convenient method for RTAs construction.[8]

The concept of moving teeth using removable appliances analogous to clear aligners has been a part of the orthodontic practice for decades to facilitate mild to moderate tooth movements.[2, 9, 10] However, the efficacy of tooth movement with clear RTAs was also lower than with fixed appliances.[8] Moreover, the removable aligner shows a different orthodontic force compared to arch-wire and brackets due to rebound force, making orthodontic treatment difficult in severe malocclusions because it cannot control the movement of the teeth as the orthodontist intended.[2, 8, 11] Therefore, a proper orthodontic treatment using these RTAs alone is not achieved as it is difficult to predict the movement of teeth in the course of the treatment. [8, 11] As a result, it was stated that the use of auxiliary devices such as attachments and inter-arch elastics is required to improve the predictability of teeth movement during orthodontic treatment.[3, 11, 12]

The use of attachments of different thicknesses and shapes in combination with an aligner was conducted to help the movement of specific teeth in various directions.[8, 13] However, in orthodontic treatment, various movement mechanisms such as extrusion, intrusion, rotation, and torque are applied, and the positions of the attachments attached to the surface of the teeth vary.[8, 14] However, the effectiveness of these attachments at specific orthodontic treatment stages depends on the movement mechanism and the position of the attachments.[15, 16] Therefore, there is a need for a comparative analysis of the various positions of attachments fixed on the teeth surface and the movement mechanism of teeth at each orthodontic stage, as well as an analysis of the distribution of stresses that are delivered to the inside of teeth.[8, 17]

For several decades, 3-D simulation analysis was widely used in the field of dental research by building a hypothetical 3-D FE model assuming the dental treatment conditions. [18] FEA is a non-invasive virtual model, it has the advantage of being able to forecast the results without direct application to patients. In addition, FEA allows analysis to be conducted by simulating the technical method and environments that are difficult to apply in an actual clinical setting. [8, 19]

The current study was conducted to simulate various shapes and positions of attachments for the extrusion orthodontic treatment scenarios of maxillary central incisor using the FEA to originate the optimum shape of attachment for each condition and to analyze the best position for attachments by simulating diverse attachment positions for each attachment.

Materials and Methods:-

This study was designed as an in-vitro experimental 3D FEA comparative study.The current FEA study was carried out at National Research Centre (Cairo, Egypt).This study was conducted toidentifythe optimal attachment designs (square, round, and triangle) and position with RTA during extrusion movement of a maxillary central incisor model tooth using FEA.Specimens preparation was performed as 3D finite geometric models.By using actual load and boundary conditions, the FEA employed in this study created a virtual 3D simulation model that makes it possible to forecast the outcomes. This study did not employ statistical analysis; instead, it produced and compared each model's single value because it can compare and examine the stress distribution and displacement values according to changes in design because all parts were constructed using the same FEA. A total of 9 runs were performed on the 3 attachment models (3 runs per model) to determine the stresses and displacement in each model at 3 different positions (incisal, middle, and gingival) as follows:

Constructing attachments:

For extrusion tooth movement that takes place during orthodontic treatment, different attachment forms were created using the program (Solid-works). Three squares, round, and triangle attachment forms with dimensions of 1 mm by 1 mm by 0.85 mm (length, height, thickness) were among the shapes used for extrusion. Extrusion attachments have the same forms, but because the teeth travel in different directions, the attachments were placed by the direction of movement of the teeth. The surfaces to which load was applied were classified as having an angle of 90 degrees to the attachment surface of the teeth.[8, 17, 20] (Figure 1)

Fig. (1):- Attachment design for extrusion.

Determine the ideal shape of attachments for each orthodontic treatment scenario using FEA:

To examine the ideal shape of numerous attachments assuming each orthodontic treatment scenario, bone and tooth shapes were created. Instead of being taken from CBCT images of real patients, the shapes of bone and teeth applied to each attachment were identical, and simplified shapes were used. The teeth portion was built using the teeth and the PDL, and the bones were divided into cortical and cancellous bones. The PDL and cortical bone thicknesses were fixed at 2 mm and 0.2 mm, respectively, based on an earlier study by Kim et al. (2020) [8].**(Figure 2)**

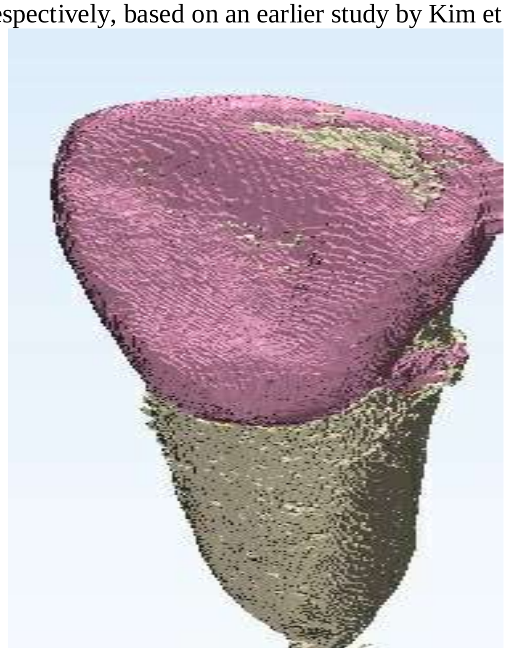


Figure (2):- Geometric tooth model.

Mesh construction:

All materials utilized in this present study were assumed to be isotropic, homogenous, and retain linear elasticity, and their assigned properties were listed in **Table (1)**. The teeth portion was built using the teeth and the PDL, and the bones were divided into cortical and cancellous bones. The PDL and cortical bone thicknesses were fixed at 2 mm and 0.2 mm, respectively.Removable thermoplastic aligners were applied with a thickness of 0.3 mm for each orthodontic treatment scenario. Then, the material characteristics of each component were applied.It was decided that 0.05 mm would serve as the attachment's minimum and maximum settings. For the cortical bone, cancellous bone, and PDL models, the corresponding numbers of elements and nodes. These numbers were used uniformly throughout all models. (**Figure 3**).In contrast, the elements and nodes for teeth, RTA, and attachments changed depending on the movements of the extrusion tooth.A friction coefficient of 0.2 was applied by assuming a sliding condition for the surface of contact between RTA, teeth, and attachment in the two orthodontic treatment models, as opposed to "tie contact," which assumed a perfect union and bonding state among bone, teeth, PDL, and attachments. The side and bottom of the bones were entirely controlled by the two orthodontic treatment models, preventing rotation and/or movement in other directions.The load was applied by regulating the displacement of the RTA, which produces the displacement of the teeth. Extrusion orthodontic treatment models applied load using displacement control. On the y-axis, the extrusion model was moved 0. 5 mm in the positive direction. Tetrahedral elements were used to create each component. While the minimum and maximum mesh sizes for the PDL and attachments were set to 0.5, the mesh sizes for the cortical bone, cancellous bone, mucosa, and teeth were designed to range between 0.5 mm and 1mm.

Table (1):- Properties of different materials used for the construction of finite element models:

Components	Young's Modulus (MPa)	Poisson's Ratio
Cortical bone	13,700	0.3
Cancellous bone	1370	0.3
Mucosa	3.45	0.45
Teeth	20,000	0.3
RTA	2050	0.3
Attachment	12,500	0.36

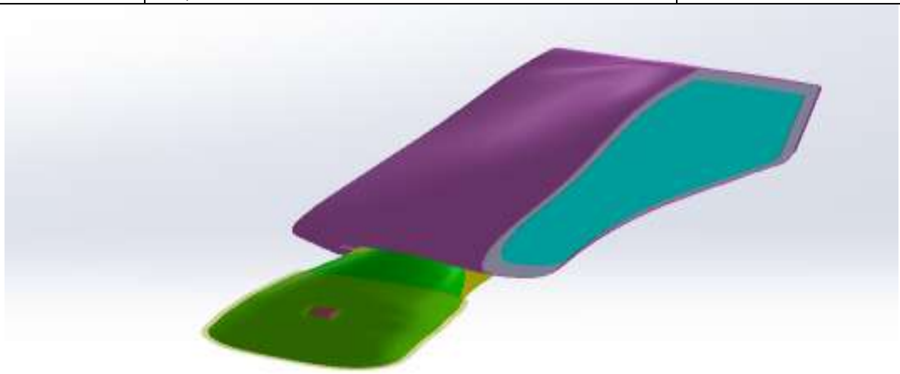


Figure (3):- Screenshots for meshed model components (a) RTA, (b) attachment, (c) tooth structure, (d) spongy bone, (e) cortical bone.

Building a maxillary central incisor FE model while taking different attachment positions into account for each orthodontic situation:

Using the maxillary CBCT image from earlier studies, a 3D finite element model was simulated after deriving the best attachment shapes for each orthodontic treatment scenario based on the outcomes of the FEA of the simplified orthodontic treatment model.This work created a maxillary central incisor model and ran FEA. The cortical bone, mucosa, and PDL all had thicknesses of 2 mm, 2 mm, and 0.2 mm, respectively. The maxillary central incisor was isolated from the maxillary CBCT picture and used as a single tooth shape to compare displacement according to the position of attachments. (**Figure 4**)

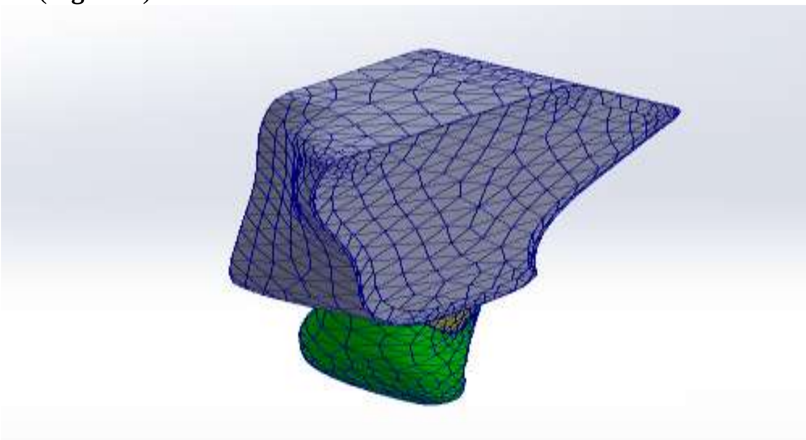


Figure (4):- The creation of a 3D maxillary FE model that incorporates the attachments, cortical bone, cancellous bone, mucosa, and teeth

Loading and boundary conditions:

A line connecting the locations of the buccal and lingual sides on the tooth at the y-axis was drawn from the buccal side to the lingual side to measure the change in angle after the load was applied. Three attachment sites (incisal, middle, and gingival) for extrusion and intrusion were taken into consideration in order to examine the biomechanical characteristics of the maxillary central incisor's teeth based on the placement of the attachments affixed to the teeth. (**Fig. 5)** To ensure that movement did not happen on either side of the elements of cortical bone, cancellous bone, and the mucosa, all FEA models by tooth movements and attachment positions were entirely limited. The nodes between neighboring parts were combined using the "tie contact" condition, however, the combination condition between the teeth and the attachment assumed connection by resin. This is because the bone and the mucosa, bone, and PDL, as well as the PDL and the tooth, are connected as one. Based on the contact surface applied to each attachment, the load was applied. On the attachment's contact surface, loads in Newton that caused 0.5 mm in the central incisor teeth were applied. (**Figure 5)**

After placing the load, the Peak von Mises stress (PVMS) produced in the bone, teeth, PDL, RTA, and attachments was measured for comparative analysis according to the geometry of the attachment by each orthodontic application. Additionally, the PDL was used as a reference for dividing the teeth into upper and lower sections so that the maximal displacement could be measured in each location. The PVMS values in the attachment, the teeth, and the values of teeth displacement (mm) were compared and examined after the load was applied to the attachment in order to determine the best position for each attachment.

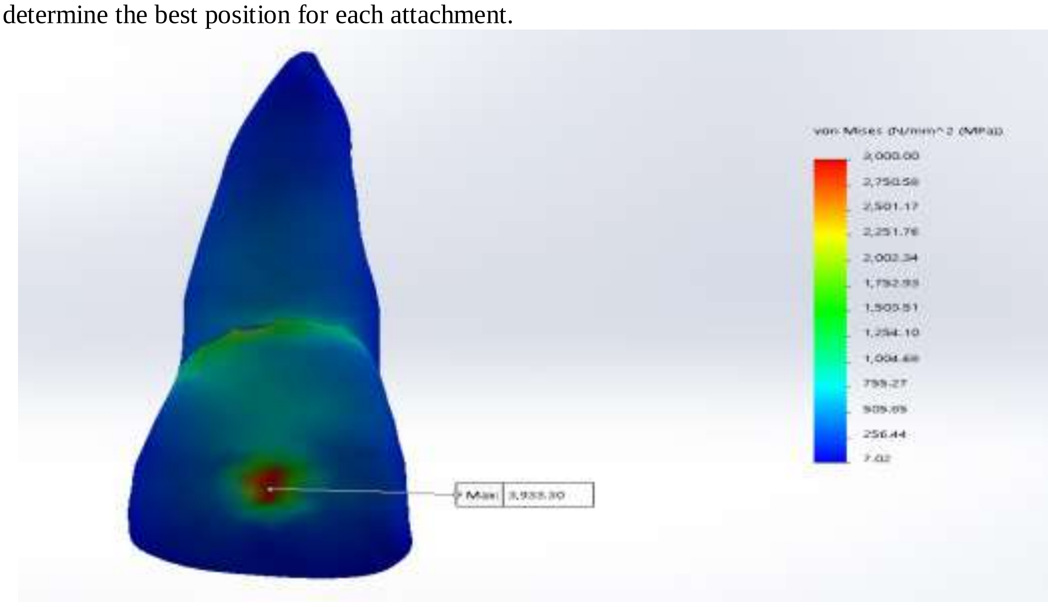


Figure (5):- Building of the treatment model considering different attachment positions on the teeth caused by two tooth motions; (a) extrusion attachment, and (b) intrusion attachment.

Results:-

The FEA outcome for different attachment shapes:

The attachments for extrusion simulation results were evaluated using the PVMS values and contact forces at the 0.5 mm extrusion displacement values in the upper and lower regions of the maxillary central incisor's teeth. (**Figures 6 and 7**)Extrusion for square shape attachment, extrusion for round shape attachment, and extrusion for triangle shape attachment revealed comparable PVMS results without significant differences for the bone, teeth, and PDL. The round shape attachment shows the lowest PVMS measurement for the bone, teeth, and PDL. While the square shape attachment had the highest showed the higher PVMS measurement for the bone, teeth, and PDL, followed by the triangle shape attachment with PVMS measurements for the bone, teeth, and PDL. Additionally, the results of FEA demonstrated that, among all examined RTA attachments, the round shape attachment had the lowest PVMS values and contact forces during extrusion movement, whereas the square shape attachment had the highest PVMS and contact forces followed by the triangle shape attachment but without significant difference.

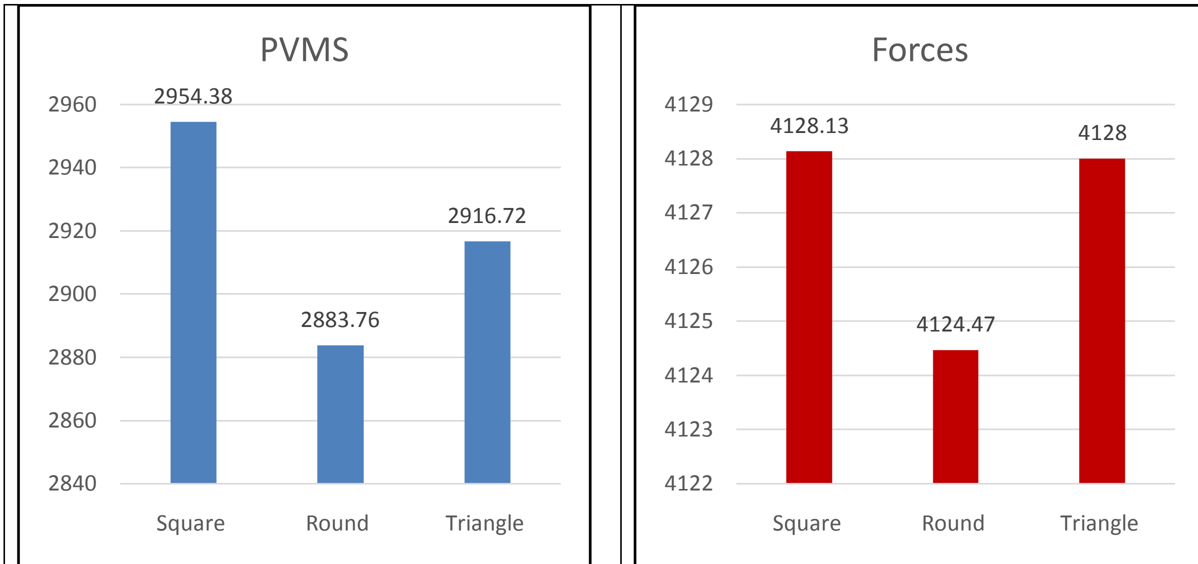
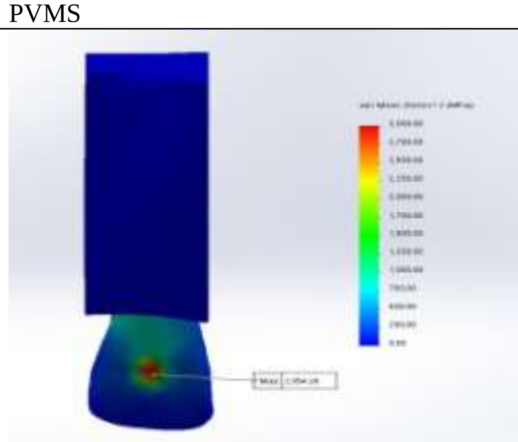
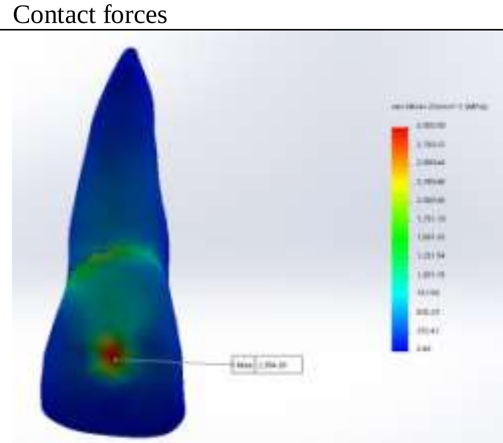
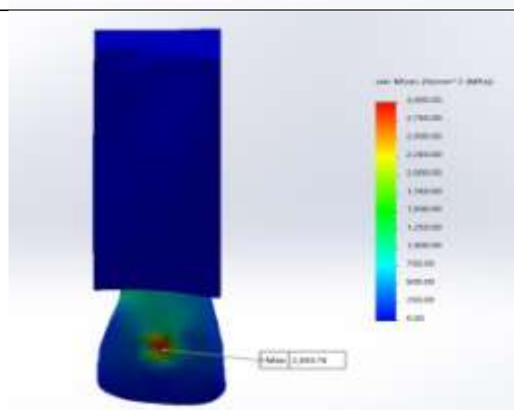
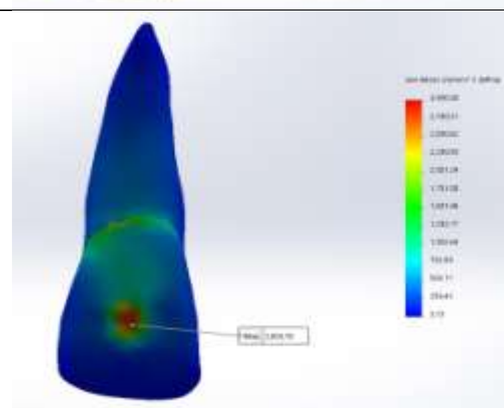


Fig. (6):- The PVMS and contact forces values of extrusion for the three attachments at 0.5 mm displacement.

Attachment	PVMS	Contact forces
Square		
Round		

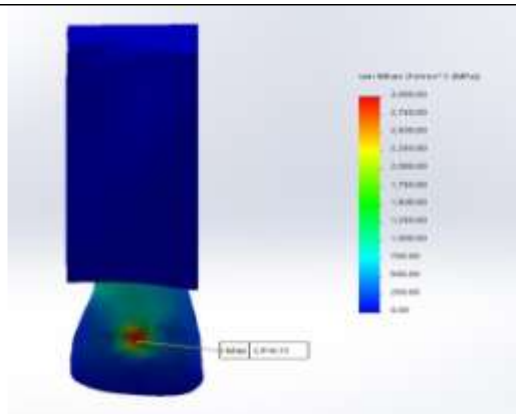
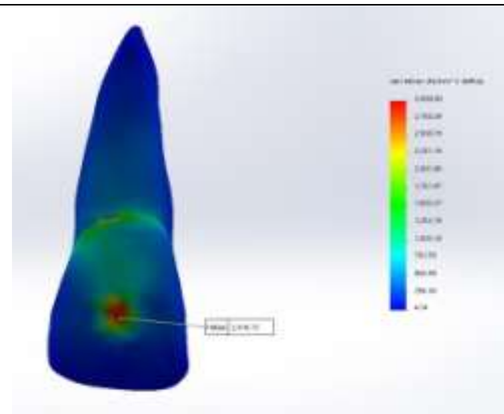
Triangle		

Fig. (7):- FEA models showed PVMS and contact forces during extrusion movement for 0.5 mm displacement in bone, teeth, and PDL.

Results of FEA to determine the optimal attachment position:

The FEA results revealed that the PVMS values of all examined RTA attachments reduced as the attachment location went from the incisal to the gingival positions of the teeth at the buccal side, according to the extrusion attachment model. (**Table 2**) However, the FEA results revealed that the displacement values of the maxillary incisor teeth were increased in contrast to the stress distribution patterns of the attachment position during the extrusion displacement of the central incisors teeth. That means the higher displacements values in the teeth resulted from the lower PVMS of the attachment. (**Table 3**)Additionally, the outcomes of the FEA were comparable for all regions of the maxillary incisor teeth's lingual and buccal sides for both attachments and teeth during the extrusion tooth movement. (**Tables 3 and 4**) and (**Figure 8**)

Table (2):- The PVMS attachment results during extrusion movement for different attachment designs:

Variable	**PVMS (MPa)**					
	Square		**Round**		**Triangle**	
	(Buccal)	(Lingual)	(Buccal)	(Lingual)	(Buccal)	(Lingual)
Incisal	238.436	238.424	236.543	236.538	233.433	233.423
Middle	232.221	232.215	228.212	228.198	227.021	227.018
Gingival	229.234	229.221	227.321	227.298	225.213	225.197

Table (3):- The PVMS maxillary incisors teeth results during extrusion movement for different attachment designs:

Variable	**PVMS (MPa)**					
	Square		**Round**		**Triangle**	
	(Buccal)	(Lingual)	(Buccal)	(Lingual)	(Buccal)	(Lingual)
Incisal	46.232	46.227	45.976	45.964	45.895	45.888
Middle	47.386	47.376	46.989	46.975	46.878	46.869
Gingival	48.231	48.226	47.987	47.974	47.789	47.778

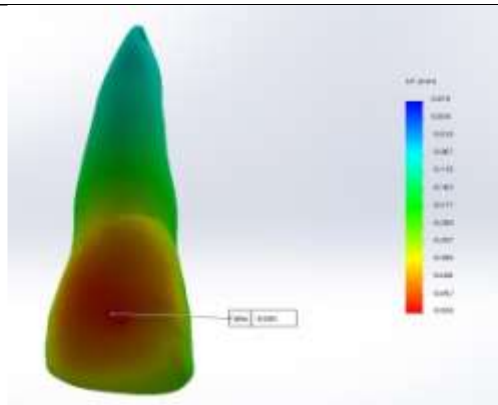
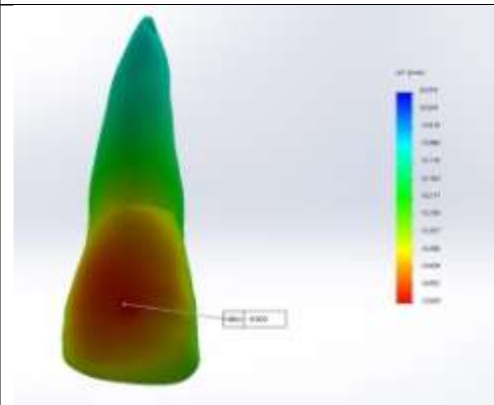
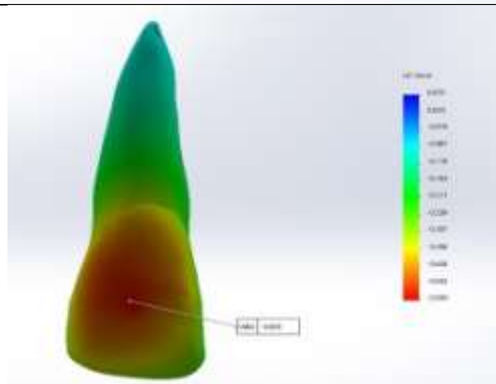
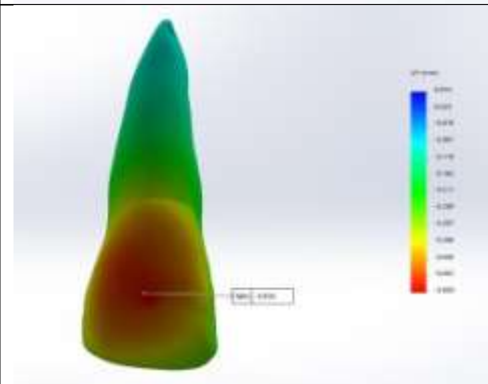
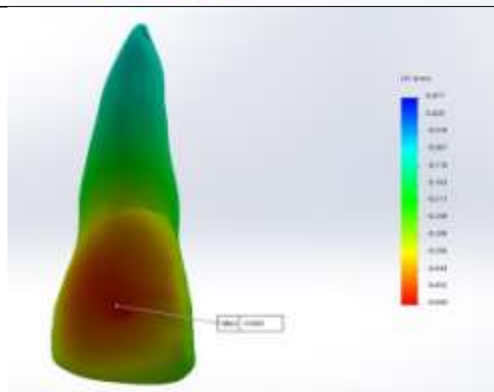
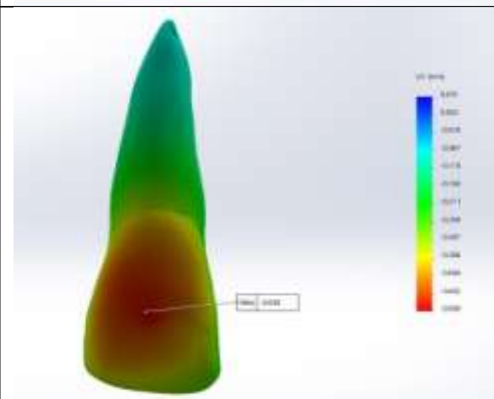
Attachment	Attachment	Teeth
Square		
Round		
Triangle		

Fig. (8):- The FEA model for teeth displacement patterns in various attachment models.

Discussion:-

The objective of the current study was to evaluate the effectiveness of different attachment systems as well as different attachment positions on the intended extrusion tooth movement for RTAs.In this present study, the RTAs were chosen because it was found that the development of RTA on the basis of CAD/CAM has improved the effectiveness of conventional orthodontic treatment. In the use of an RTA, the orthodontic treatment device can be produced after creating virtual orthodontic stages using CAD software. [8]Furthermore, Buschang et al. (2013) [21] evaluated the time efficiency of RTAs and fixed appliances, and they discovered that RTA therapy needed much fewer visits, emergency visits, chair time for emergencies, and total chair time than fixed appliances. The treat root resorption, according to an earlier investigation by Eissa et al. (2018) [22], when the RTA was used with periodic loading.

However, because an RTA cannot regulate the movement of the teeth as the orthodontist intended, orthodontic treatment is challenging in severe malocclusions compared to archwire and brackets because of rebound force. [23]However, in orthodontics, it is believed that the RTA treatment approach cannot generate sufficient load for teeth to move effectively and steadily. [24, 25, 26] Because it is challenging to predict how the teeth will move during therapy, correct orthodontic treatment cannot be performed in a treatment process employing RTA alone. [8, 22]

In this current investigation various attachments were used with the RTA this is because it was reported that, in order to increase the predictability of teeth movement during orthodontic treatment, auxiliary devices including attachments and interarch elastics are reportedly needed according to Rossini et al. (2014) [27]. Moreover, in this current study different attachment positions were used this is because it was established that however, the effectiveness of these attachments at specific orthodontic treatment stages depends on the movement mechanism and the position of the attachments.[28]

Building a fictitious 3D FE model while assuming the surgical and dental conditions has been a common practice in the field of dentistry research for several decades.[24, 27, 28] In particular, the FEA is a virtual model that is non-invasive and has the benefit of being able to anticipate the outcomes without being directly applied to patients.[8, 27, 28] Additionally, it enables analysis by imitating the procedural approach and context, which are challenging to use in a real-world clinical situation.

Additionally, using RTA alone could cause movement that the orthodontist did not anticipate. For these reasons, earlier research used the FEA to conduct biomechanical assessment and analysis on RTA and attachments, which indicated that attachments caused teeth to move more effectively. [24, 26] As it was stated that the shape and the position of the attachment are determined by the orthodontist as well as the dental technician according to Kim et al. (2020) [8]. Therefore, in this current investigation, we determine the amount of intended displacement in order to determine the optimal shape and locations of attachment for efficient teeth extrusive and intrusive movement when employing the RTA for orthodontic treatments.

In this current investigation, extrusion and intrusion load for the attachments were applied using displacements of 0.5. In earlier research by Gomez et al. (2015) [24], the severe PDL deformation in the extrusion attachment model prevented the analysis from converging. As a result, it has been established that the stresses and strains produced in the PDL in earlier research and in this investigation are different.

The FEA results revealed that stress was concentrated at attachment corners that receive a load from RTA and attachment surfaces that attach to the teeth in the comparison of the PVMS for extrusion attachment. Particularly, the square attachment demonstrated higher PVMS and contact forces when compared to other shapes, and it is expected that the attachment will likely experience a higher rate of failure or separation. Contrarily, compared to other shapes, the attachment of the round shape displayed the lowest values of the PVMS and contact pressure. These results agreed with the results of the previous study by Kim et al. (2020) [8] who found that the attachment of a square shape induces higher PVMS and contact pressure values when compared withtriangular and round shapes as well as the round shape attachment induces the lower PVMS and contact pressure values.Moreover, Savignano et al. (2019) [26] found that the rectangular palatal attachment can enhance the efficiency of the appliance for the extrusion of an upper central incisor, according to FEA results in comparison withrectangular and ellipsoid buccal attachments.

However, the results of extrusion movement in this current investigation showed comparable values for PVMS and contact pressure values for 0.5 mm displacement. These FEA results suggested that the round-shaped attachment was projected to be the most suitable attachment form for extrusion and intrusion maxillary incisor tooth movements due to the lower risk of fracture and desired stress distribution.[8] However, these results are in disagreement with the results of the previous study by Kim et al. (2020) [8] who found that the square shape attachments produce twice higher PVMS and contact pressure values in comparison with round shape attachments. This is because the PVMS, as well as contact force values, were comparable in this present study.

Furthermore, in this current investigation, the FEA of orthodontic treatment was carried out considering some attachment positions as secondary objectives after determining the optimal shape of attachment for each orthodontic condition. The PVMS values of the teeth and attachment in the case of extrusion were lowest when the attachment was placed at the gingival area of the buccal and lingual sides of the teeth, and the teeth movement was also greater than in other attachment positions. Although the gingival position had the highest attachment and tooth motions during extrusion tooth movement, those in the center position were comparable to those in the gingival and incisal regions. Therefore, based on the finding FEA results we could expect that placement of the attachments on the tooth surfaces will work best if they are placed in the lower part of the tooth's anterior in cases of extrusion and in the incisal part of the anterior in cases of intrusion. However, these results are in disagreement with the results of Kim et al. (2020) [(8)] this could be attributed to the different tooth (canine) utilized in their study.

Conclusion:-

According to the results of the current FEA investigation,the round-shaped attachment was predicted to be the most acceptable attachment form for the extrusion of maxillary incisor tooth movement. Additionally, when doing central incisor extrusion, the lower middle position is ideal.

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