OPTIMAL PERCENTAGE OF BUCCAL TO PALATAL INTRUSIVE FORCE RATIO FOR PURE VERTICAL MAXILLARY FIRST MOLAR INTRUSION: A FINITE ELEMENT STUDY

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ABSTRACT

Objective: Aiming to find mathematical criteria for determination of tension forces on both sides' brackets to ensure vertical intrusion of upper first molar. **Materials and Methods:** A 3D finite element model was built for upper first molar by laser scanning of natural extracted tooth. The modeled tooth was placed in a simplified bone model. Palatal and Buccal brackets were modeled on engineering CAD software then placed on the scanned tooth to apply the tensile forces on them. Stepped loading cases were analyzed, for total 200gm (2N) intrusive force started by equal tension force of (1N) on each side. A gradual reduction of force magnitude from palatal side tension was applied to obtain a more homogenous stress distribution to determine the suitable ration between both sides. **Results:** The stepped analyses showed that; applying load of 1N (100gm) buccally and gradual reduction of the applied force magnitude from palatal side resulted in using of 0.80N palatal will be the most suitable value to ensure pure vertical intrusion. This ratio was correlated to tooth geometry by FEA to conduct the aimed criterion. **Conclusion:** Applying palatal side tension force of order 80% of the buccal side tension force may insure pure vertical intrusion of upper first molar. This empirical ration may slightly differ among patient's age, sex, and ethnic groups due to changing in tissue characteristics and tooth geometry.

KEYWORDS: Upper first molar intrusion, TADs, finite element analysis.

INTRODUCTION

Posterior molar intrusion is essential for treatment of many orthodontic problems, as: anterior open bite, steep mandibular plane, increased anterior facial height and extruded posterior molars [1–2].

To avoid unwanted tooth movements and root resorption, the suitable orthodontic intrusive force must be precisely measured[3].Two-dimensional cephalograms are thought to be inadequate for evaluating positioning changes of teeth following intrusion, while three-dimensional tooth movement may create mistakes due to short distances being assessed in the radiograph[4].example Lascala et al2004 [5] used 2mm diameter metal markers on dry skulls and CBCT and reports errors in linear accuracy 2 to 3 mm at the maxillofacial region.

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Mini-screw as orthodontic anchoring was proposed by Kanomi and Costa et al [6]. Since then, many authors have utilized mini-screws as skeletal anchorage for molar intrusion this improvement of orthodontic skeletal anchorage is considered essential for supporting intrusion and allows for simpler orthodontic treatment [7-11].

The incorporation of dental implants and TADs into orthodontic therapy allowed for unlimited anchorage, (zero anchorage loss) [12–14]. Single-sided buccal or palatal pressure causes tooth tilting in the direction of force application thus, the application of intrusion forces from both sides (buccal and palatal) resulted in a more equal stress distribution and allowing for vertical resultant movement[15].

Several investigators studied the stresses induced in bone around mini-implant with different techniques; however, there is little information available regarding intrusive mechanics. Finite element analysis (FEA) permits the systematic application of diverse force systems at any point and in any direction, as well as the quantitative assessment of such forces [16].

A FEA successfully utilized in orthodontics and considered a good tool to evaluate stresses due to orthodontic forces since in-vivo investigations cannot reveal the biomechanics inside the bone tissue [17, 18] so FEA is recognized as a relevant and noninvasive approach to realistically examine stress distribution [19].

Intrusive mechanics of maxillary molars can be obtained via Several protocols anchored with mini-implants [20-22] however, because the upper first molar has two buccal roots that are relatively smaller than the palatal root, there is some concern about the best protocol to perform molar intrusion with maximum efficiency and pure vertical intrusion by adjusting the ratio of buccal to palatal intrusive force level using FEA.

The present study was conducted to evaluate the optimal relative percentage of buccal to palatal intrusive force ratio which could produce pure vertical maxillary first molar intrusion without any buccal or palatal molar tipping by balancing the outer and inner intrusive force ratio using finite element analysis (FEA) as no previous researches−tried to calculate such an important ratio.
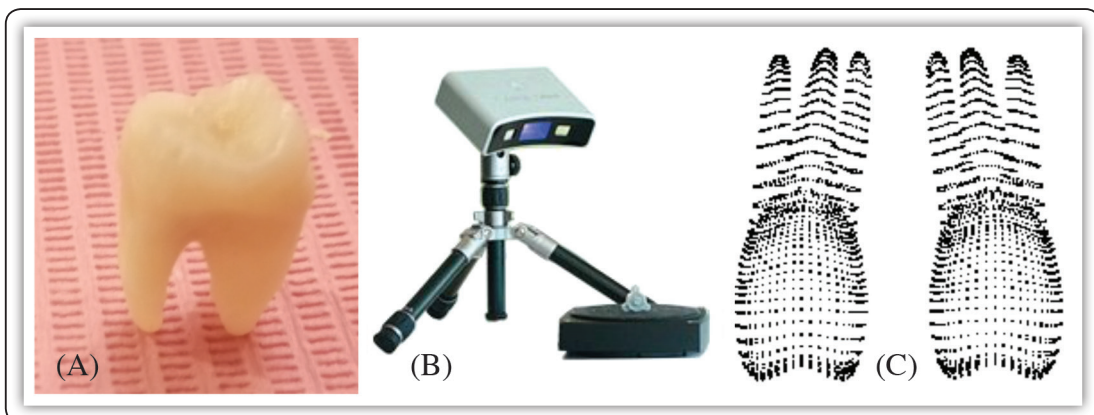

FIG (1) (A) Natural upper first molar.   (B) Laser scanner   (C) Cloud of points

MATERIALS AND METHODS

A finite element model for upper first molar was developed by laser scanning for extracted sound tooth (Figure 1A) after patient acceptance. The tooth geometry was acquired by laser scanner (Geomagic Capture, 3D Systems, Cary, NC, USA) (Figure1B). Such scanner type produced data file containing a cloud of points coordinates, as illustrated in (Figure 1C). An intermediate, software was required(Rhino 3.0 - McNeel inc., Seattle, WA, USA) to create and trim surfaces by the acquired points (Figure 1C). Then, the solid (closed) tooth geometry was exported to finite element program as STEP file format [23].

Measurements on the scanned tooth indicated that; buccal root length was of 13mm length while the palatal ones were 10 and 10.5mm, while the roots side areas were 0.1297, 0.03865, and 0.1885 respectively. Buccal to palatal roots side area ratio was of order 57%, on the other hand, the cross sectional areas ratio was about 66.69% buccal to palatal. Additionally, the root resting area on bone at furcation was divided as 34% buccal root, 51% palatal roots, and 15% for connections between the three roots.

On the other hand, cortical and cancellous bone models were created using engineering commercial computer-aided design software AutoDesk Inventor version 8.0 (Autodesk Inc., San Rafael, CA, USA). The bone geometry was simulated as bill shape, where thin shell of 1 mm represents cortical bone was filled by cancellous bone [24].

The scanned tooth geometry was set in place as its natural position (5° tilted in Mesial direction, and 9° tilted in Palatal direction). Then, set of Boolean operations on ANSYS environment (ANSYS Inc., Canonsburg, PA, USA) were performed to create enamel layer, and roots cavities in bone and then finalize the model. All materials which fed to ANSYS were considered homogenous, linear and isotropic as reported by Hamed H.A 2018 [25] and listed as

Young's modules [GPa] and Poison's ratio; Titanium: (110.0) (0.34), Dentine: (18.6) (0.31), Enamel: (84.1) (030), Cortical bone: (13.7) (0.30) and Cancellous bone: (1.37) (0.30) respectively.

The meshing of the models' components was done by 3D brick solid element "187" which has three degrees of freedom (translation in main axes directions) [26]. The resulted numbers of nodes and elements are listed in (Table 1) and the meshed model components are presented as screenshots from ANSYS in (figure 2 a, b, c, d, e, f, g, h.)

TABLE (1) Mesh density of the two models' components

Material	Number of elements	Number of nodes
Buccal bracket	6,159	9,875
Palatal Bracket	9,395	13,822
Dentine	239,300	340,056
Enamel	29,272	48,968
Cortical bone	66,015	109,349
Cancellous bone	341,116	484,288
Total	691,257	1,006,358

The final model was verified against similar one[24] and showed very good agreement in results. The research planned to start searching from maximum equal intrusive forces from both sides using 1N on each side with total 2N intrusive force that did not exert maximum compressive stresses on bone. The loading cases were planned to reduce palatal side force gradually with decreasing steps to locate the most suitable value ensuring vertical intrusion. The vertical intrusion can be indicated by equally distributed strain around the bone/tooth interface. The top plane (area) of the model was considered fixed in the three directions as a boundary condition. Linear static analyses were performed on a personal computer (Intel Core i7 processor, 2.4 GHz, 6.0 GB RAM), using commercial multipurpose finite element software (ANSYS version 16.0).
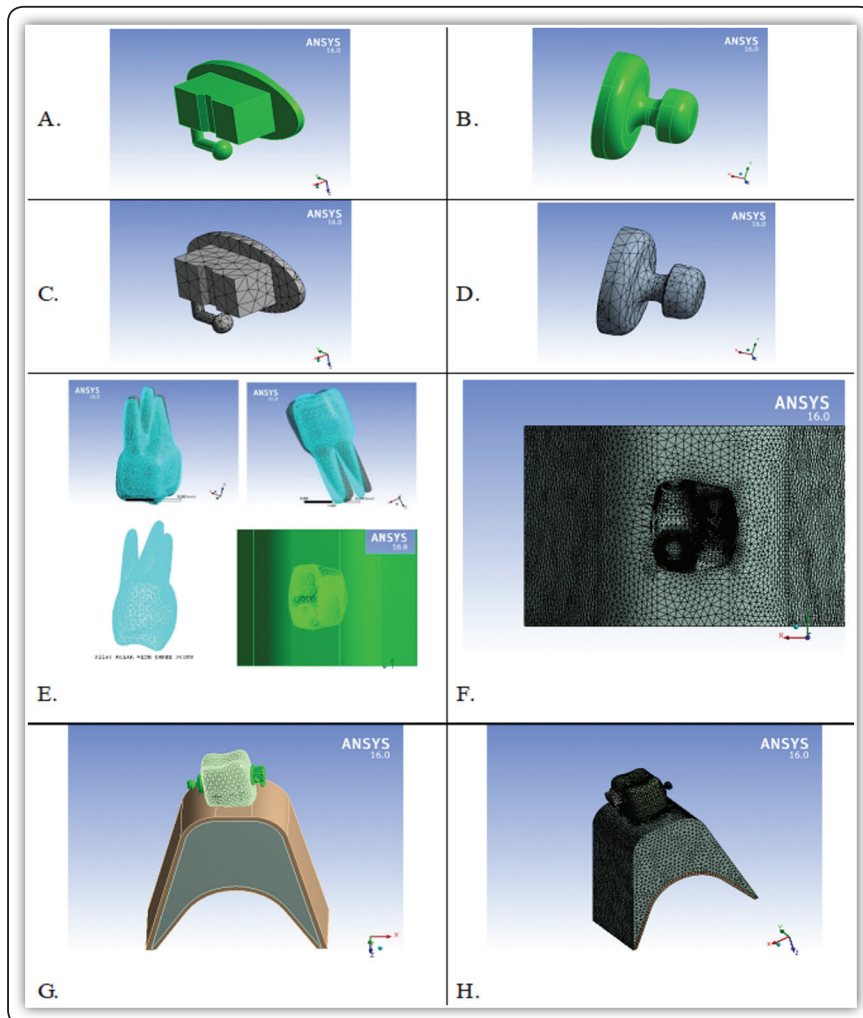
FIG (2) (a, b, c, d, e, f, g, h):

model components and its mesh:(2A) buccal bracket, (2B) lingual bracket, (2C) meshed buccal bracket, (2D) meshed lingual bracket, (2E) Scanned tooth angles, and bone "cortical and cancellous bone" top view, (2F) meshed bone "cortical and cancellous bone" top view, (2G) final model, (2H) meshed final model.

RESULTS

Starting by tension force of 5N from each side (buccal/palatal) showed close results to that reported by Sugii et al (2018)[15], where any minor differences may be referred to tooth geometry, mesh density and analysis software(s) accuracy. This trial was fair enough to verify the new model.

As the maximum obtained Von Mises stress on bone was of order (8.4 MPa) and as the analysis is performed within the linear part of all materials represented in this study, a sudden jump to 1N tension force from each side resulted in obtaining maximum Von Mises stress on bone was of order (0.016 MPa). For each loading case, minimum principal (compressive) stress to be compared to blood pressure in order to ensure being within acceptable physiological margin. Series of six loading cases as;

(1) 1N / 1N, (Fig3 a, b)

(2) 1N / 0.92N, (Fig3 c, d)

(3) 1N / 0.84N, (Fig3 e, f)

(4) 1N / 0.80N, (Fig4 a, b)

(5) 1N / 0.76N, (Fig4 c, d) and

(6) 1N / 0.72N, (Fig4 e, f) buccal / palatal loading were tested within this study.

Figure 3 and 4 demonstrate minimum principal (compressive) stress distribution on bone and
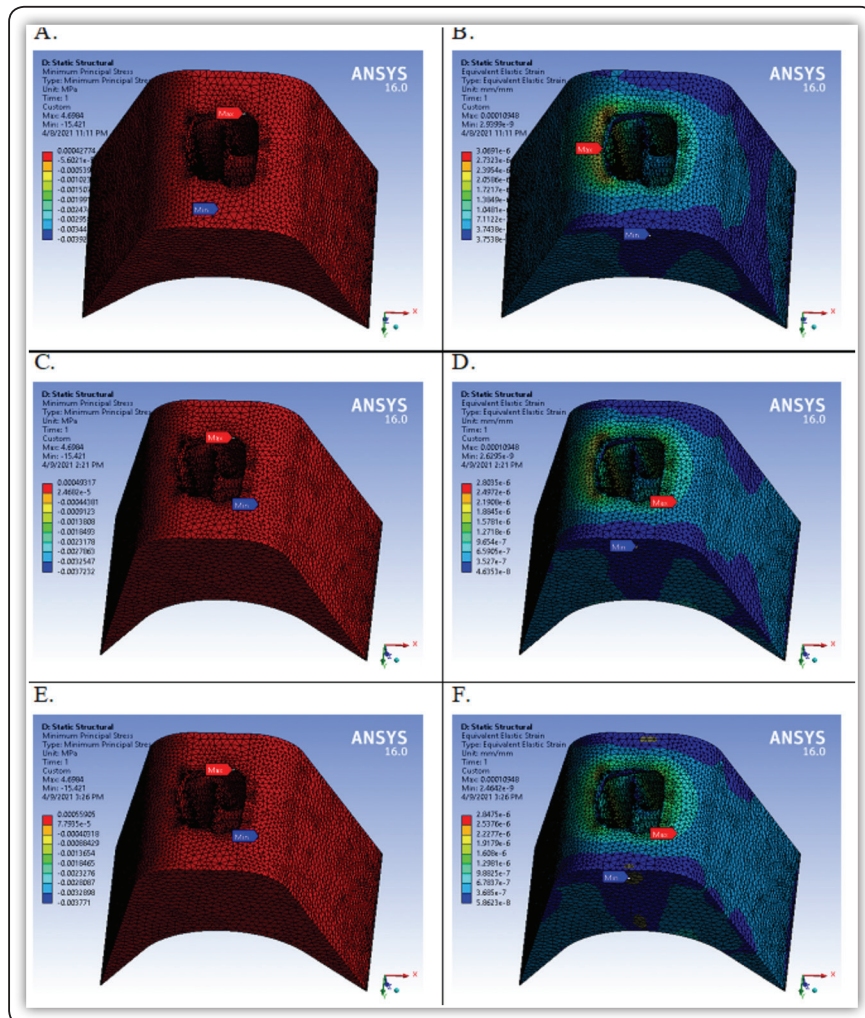
FIG (3) (a, b, c, d, e, f):

Minimum principal stress and equivalent elastic strain on bone under buccal / palatal loading; (a, b) 1N / 1N, (c, d) 1N / 0.92N, (e, f) 1N / 0.84N.

equivalent elastic strain distributions on bone in six analyses, where compressive stress used to intrude the upper first molar vertically; equivalent elastic strain distribution should show equal distribution (rings) at tooth / bone interface area to ensure pure intrusion without any buccal or palatal tipping.

Case of 1N to 0.80N (Figure 4 a, b) showed the aimed strain distribution (like rings), which may be correlated to side and cross section areas of all roots, thus the aimed ratio will be of order 80%.

Figure 4 showed two parts(or sides), the left hand side (LHS) that gradually showing the compressive stress distribution and its changes with changing loading values. Location of critical value (blue arrow) moved to be between the two palatal roots (Figure 4 a) make it safe from failure by time which is usually occurred when it located at any root tip (due to bone resorption).

The right hand side (RHS) part of Figure 4 showed the equivalent strain on bone, where with changing loading values the equally distributed strain (rings) appeared on (Figure 4 b). Red arrow indicating the extreme value of equivalent strain location between the two palatal roots might insure vertical intrusion at palatal side. Thus, the best results obtained to ensure vertical intrusion was found to be 1N to 0.80N (buccal to palatal) as presented in (Figure 4a &b).
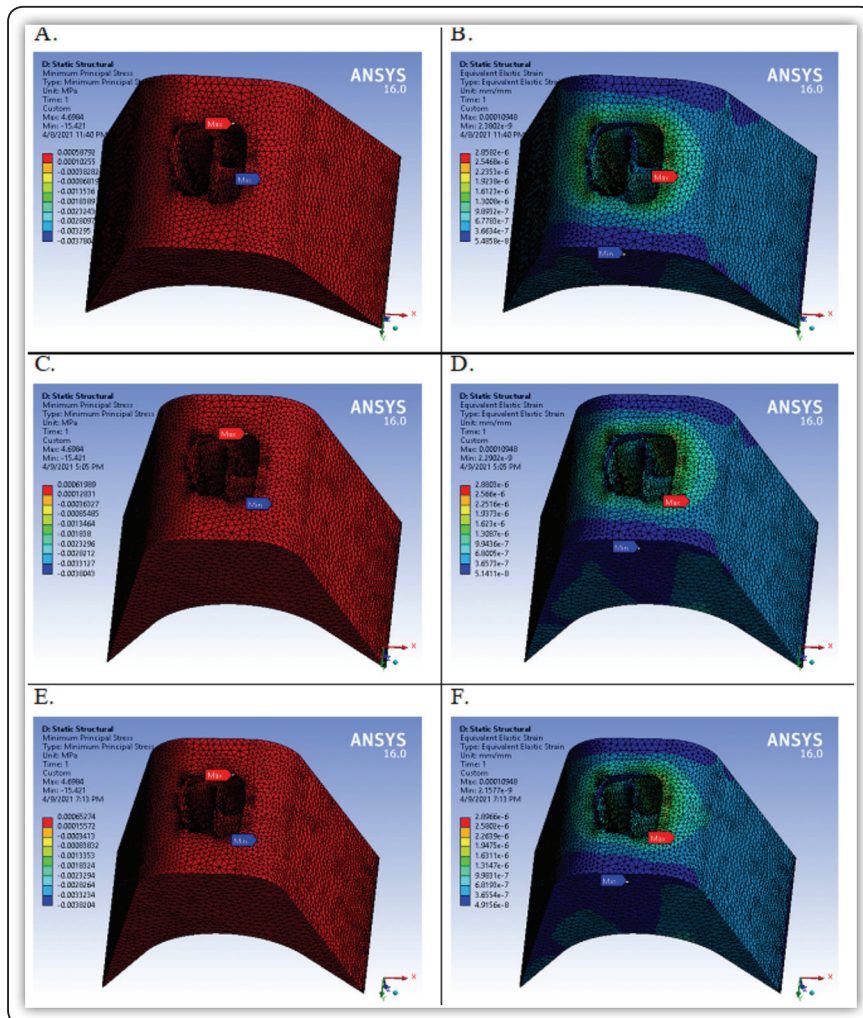
FIG (4) (a, b, c, d, e, f, g, h):

Minimum principal stress and equivalent elastic strain on bone under buccal / palatal loading; (a, b) 1N / 0.80N, (c, d) 1N / 0.76N, and (e, f) 1N / 0.72N.

Empirical relation:

Based on the obtained results from the different analyses performed within this study, and correlating results to tooth geometry, empirical relation can be extracted as follows;

Intrusion and stability of cylindrical bodies (implants or roots) inside another body (material) depends on both compression and shear forces. These forces are directly correlated the cylindrical bodies side and cross sectional areas.

As the roots side areas and roots cross sectional areas ratio between buccal to palatal sides were 57% and 66.69% respectively, thus a combination of these values can indicate the force ratio.

The empirical relation can be stated as:

Side areas ratio (buccal / palatal) + one third of cross sectional areas ratio (buccal / palatal) = inverted ratio (palatal / buccal) of the applied of loading

By numbers; 57% (buccal to palatal) + 22.22% (buccal to palatal) = 79.22 (nearly 80% palatal to buccal)

Buccal to palatal intrusive force relation calculation:

As the typical value for loading varies between 150 to 200gm forces, the applied load should be of order 83.3 to 111.1 gm buccal force and 66.6 to 88.9gm palatal force, (Table 2)

Buccal force = (overall applied load / 180) * 100

Palatal force = (overall applied load / 180) * 80

TABLE (2) The recommended values to be used in case of using 150gm or 200gm are as follows:

FEA recommendation	Buccal force /N	Buccal force /gm	Palatal force/N	Palatal force by/gm
Case of 150gm	0.8333	83.33	0.6667	66.67
Case of 200gm	1.1111	111.11	0.8889	88.89

DISCUSSION

Although alternative techniques such as photoelectric and laser holography exist, FEA was utilized in this work to measure stress and strains induced in bone the load applied to the tooth being intruded because FEA offers an advantage over other approaches since it is non-invasive, three-dimensional, reliable, and can incorporate heterogeneity of tooth structures and different orthodontic materials [16, 17, 27, 28].

Ciftera and Sarac (2011) [17] observed that buccal tilting and total stress values were evident when just trans-palatal arches and buccal force application were used for molar intrusion. Numerous earlier research reached a similar conclusion.[15,20] Baumgaertel et al 2016 [29], on the other hand, employed mainly palatal implants for intrusion and discovered considerable palatal tilting. Similarly Chan E and Darendeliler MA 2006 [30] concluded that; unilateral force accumulated the stresses near the buccal cervical area resulting in considerable tipping.

In the present study, a couple of force from buccal and palatal sides using mini-screw was used to ensure a more balanced and pure vertical intrusion which came in accordance with Sugii M et al 2018[15] and Çifter and Saraç [17] who stated that ; Single buccal intrusive force can cause considerable buccal tipping while a force couple produce more consistent force and better stress distribution in the alveolar bone and PDL making the force more perpendicular to the dental alveolus thus, promoting a more vertical intrusion.

One of the major parameters influencing the precision of finite element analysis is the number of elements and nodes constituting the models Çifter

and Saraç [17] utilized elements as small as 1.1 mm to increase the number of nodes in the critical regions where stress and displacements were measured. Therefore, in the current study, the mesh density of the model components was estimated by adding the Buccal bracket, Palatal button, Dentine, Enamel, Cortical bone, and Cancellous bone to produce 691,257/1,006,358 elements/nodes.

There have been some debates about the force magnitude necessary for successful skeletal anchorage–supported posterior segment intrusion. [31] Despite the fact that some studies did not clearly specify it, the reported force magnitudes for upper molar intrusion ranged from 150 g [13–15] to 500 g [20,32-39]. In the present study, FEA employed a total applied total molar intrusive force of 200 grams (100 g buccal and 100 g palatal), which was consistent with earlier studies[20,40-42] which concluded that; upper molar intrusion forces should be between 100 and 200 g. which also consistent with the finding of Furthermore, Kato and Kato [43] claimed that a force of 100 g was inadequate for posterior segment intrusion and that raising the force to 300 g allowed for progressive intrusion keeping in mind, this study considering posterior segment no single molar intrusion.

A similar finding was obtained by Yao et al 2005 [20] indicated a force of 150g for molar intrusion, whereas Kravitz 2007 [44] suggested a force of 100g for molar intrusion as well as a range of 200 to 400g for segmental posterior intrusion. [27] In contrast, Melsen et al. 1989 stated that mild forces of approximately 50 g were utilized for each molar intrusion.[45]

In contrast to the findings of Carrillo et al. [46], as they reported that; there was no variation in the

quantity of intrusion with various force magnitudes. Using 150 g, Xun et al. [41] obtained 1.8 mm of maxillary first molar intrusion, compared to 3.37 mm accomplished by Akan et al. [37] using 400 g for the same objective. The variations in results between different trials might be attributed to the use of mini-plates in conjunction with an acrylic. On the other hand Akl et al. 2020[27] stated that; there was no statistically significant difference in the quantity of posterior tooth intrusion between 200 g and 400g of used intrusive force.

Choi et al. 2016 [47] used FEA to examine the stress concentration in PDL, as well as adjacent cortical and cancellous bone, and determined that stresses are mostly absorbed by cortical bone. Furthermore, the stresses transferred to the periodontal ligament and spongy bone were minimal (0.01 MPa within the PDL and 705.9 to 1397.42 MPa for cortical bone), and they concluded that the maximal von Mises stress went up as the angle of insertion of the mini-screw decreased. According to the findings of Choi et al 2016[47], the PDL was not used in the current study to simplify the 3D-FEM construction as this study is a comparative research of different loading situations, the presence or absence of PDL may have no effect on the outcomes because it is a common component.

On the other hand McCormack et al 2014 [48] demonstrated that; incorporating the fibrous structure of the PDL into FE models when evaluating orthodontic pressures impacts both the amount and distribution of the strain generated in the surrounding bone. However, because of the oversimplified geometry and material characteristics of his model, the conclusions are not near to reality. In the ongoing study, the primary focus was the relative difference between the findings of two models. Therefore, excluding the influence of PDL had no effect on the results.

The majority of the published FE analyses did not account for the cementum layer around tooth roots[49] this may be attributed to its tiny thickness

and characteristics similarity to dentin so in the present study this layer was considered as a part of the dentine.

As mentioned by AbdelAzim A et al. 2014 [50], root volumes play an important role in setting the buccal and palatal force ratio. Because of the two near holes, the pressures and displacements on the cortical bone are higher in the two-implant model, resulting in a weak area in-between so considering utilizing a single broad implant or two small-diameter implants to support a crown.

While the cross sectional area should be depicted in such a way that roots are pushed to go deeply into the bone. That is, any cylindrical structure immersed in a solid medium and exposed to compressive pressures will transfer the load to the surrounding media by two mechanisms: compression and shear.[17] When applied to natural roots, this criteria might suggest lower stresses on the buccal side under equivalent compression loading on buccal/palatal attachments since each root has a smaller cross sectional area than the palatal one.

The force magnitude effective in posterior or intrusion had subjected to much debate in previous numerous studies as stated by Foot R et al 2014[31]; Tasanapanont J et al 2017 [40] used 50 gm per side; others used a force ranged from 100 to 200 gm for posterior segment intrusion [20,41-43]; arrange for 200-400 gm was suggested by . Kravitz ND et al 2007[27]; others used a heavier force range from 400 to 500 gm [31,38,39,51], So in the present study we tested a force started by 75 gm buccal and 75 gm palatal.

In the present study intrusion of maxillary first molar was tested using single buccal and single palatal implant as Paccini JV et al 2016[52] concluded that; molars can be intruded with two or three micro-implants with similar effectiveness. The maxillary molar intrusion in the present study was tested not the mandibular molar as maxillary molar can be intruded better than the mandibular one up to 4 mm as stated by numerous previous studies [34,51,53-55].

If buccal mini implant only used for molar intrusion buccal molar tipping and buccal dental arch distortion will occur so a trans palatal arch usually added to counter act this tipping force due to un balanced intrusion as said by Sherwood 2007[56] Lee 2004[9] stated that; it is difficult by using palatal micro-implant to make the force vector pass through the center of resistance due to the palatal anatomy so careful torque monitoring bucco-palatal direction is very important or using another buccal screw to counteract the palatal moment which considered more invasive; so in the present study we calculated the optimal palatal to buccal force ratio to avoid any degree of buccal tipping.

CONCLUSIONS

More homogenous stresses distribution and pure vertical upper first molar intrusion can be achieved by couple force using both buccal and palatal micro-implants with non-equal intrusive forces on buccal and palatal sides (1:0.8) respectively to equalize the roots volumes.

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