Original Article

Tooth Displacement, Stress Distribution Patterns and Changes in Centre of Resistance in Temporary Anchorage Devices-Assisted Individual Canine Retraction cases, with and without Micro-Osteoperforation

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Abstract

Background: Micro-osteoperforation (MOP) is a minimally invasive technique that can trigger an inflammatory response in the alveolar bone to accelerate orthodontic tooth movement. The procedure characteristically shortens the total treatment duration by lowering the resistance to tooth movement. **Aim**: The present study compared individual canine retraction with and without MOP in terms of tooth displacement, stress distribution patterns, position of the centre of resistance (CRes) and amount of canine retraction using the finite element analysis (FEA) model. **Materials and Methods**: An FEA model of the maxilla was created using Autodesk Inventor and Fusion 360 software programs, while a fixed orthodontic appliance was built with stainless steel metal brackets and molar bands in accordance with the MBT 0.022 -inch slot prescription for the maxillary arch. One side of the maxilla, from the central incisor to the second molar, was taken as the experimental side (with MOP), while the other side acted as the control side (without MOP). **Results**: An important finding of the present study was the change in the position of CRes of the canine which was significantly higher on the experimental side, with the corresponding tooth displacement in this case along the x-axis near CRes being 1.124 $x10^{-5}$mm, which was higher than that recorded on the control side wherein MOP procedure was not performed (-10.808 $x10^{-5}$mm). **Conclusion**: The study concluded that MOP significantly decreased the overall stresses generated in the periodontal ligament and adjacent alveolar bone. Furthermore, the CRes of the tooth moved to a more favourable position facilitating greater tooth displacement, subsequently, increasing the rate of orthodontic tooth movement.

Keywords: Tooth displacement, Stress distribution patterns, Centre of resistance (CRes), Temporary anchorage devices (TADs), Canine retraction, Micro-osteoperforation (MOP).

Introduction

Orthodontics is a specialised branch of dentistry that deals with diagnosis, prevention, interception and correction of malposed teeth and jaws. It also deals with modifying the facial growth pattern which is known as the dentofacial orthopaedics. The primary goal of orthodontic practice is the management of different types of malocclusions to improve facial aesthetics.[1,2]

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In the past, therapeutic extraction of teeth and expansion of the dental arch for gaining space in order to relieve malocclusion have always remained a controversial topic among the orthodontists.[3-5] Later, as extraction concepts evolved, space closure played a vital role in the fixed orthodontic treatment. In recent times retraction and space closure procedures during the various orthodontic treatment protocols involve placement of mini-implants in specific sites as temporary anchorage devices (TADs) utilizing bone as a source of anchorage, while minimizing unwanted anchorage loss. A TAD serves as an absolute anchorage for extraction cases where mini-implants are placed on the buccal side for retracting the anterior teeth, while this ensures an absolute translational or bodily movement of the teeth during space closure. However, orthodontists must have a thorough knowledge of the concept of biomechanics and the generated stress fields working behind such procedures.[6-10] The success of these mini-implants, largely depend on implant placement sites.

Many factors such as the proximity of vital anatomic structures, thickness of the bone, the need for anchorage and the type of forces applied have a crucial role in implant success, while the implants have to be placed 5-8mm from the crest of the alveolar bone.[11-13] Though the expected treatment outcome was achieved by fixed orthodontic therapy, prolonged treatment duration remained a major setback.[14,15] It was in this context that accelerated orthodontics evolved to decrease treatment duration without compromising the treatment outcome.[16,17] In a similar context, numerous methods were devised to increase the rate of orthodontic tooth movement by increasing the number of osteoclast and osteoblast cells, which is primarily achieved through physical, chemical and mechanical methods. While the chemical method involves the use of certain agents like parathormone (PTH), osteocalcin, vitamin D3 supplementation and corticosteroids apart from various other hormones as well as the newly introduced autacoids and cytokines which are injected directly in and around the alveolar bone to induce an inflammatory response, stimulation in the form of light, heat, magnetic fields, currents and also different types of lasers have been used in the physical method.[18-20] The mechanical methods, on the contrary, involve inducing trauma in a particular region that causes the release of cytokines and other inflammatory mediators, subsequently, increasing the rate of tooth movement. This method uses corticotomy, piezocision and micro-osteoperforation (MOP) methods principally to achieve the desired goals.[21-25]

Among these, MOP is considered to be a minimally invasive and a simple chairside adjunctive orthodontic procedure. Micro-osteoperforations are made on the surface of the buccal and lingual cortical plates alongside the desired side of orthodontic tooth movement to accelerate the process.

This procedure has numerous advantages to its credit with the main advantages being that it consumes less time, while it can be performed during any stage of orthodontic treatment to accelerate tooth movement with no discrete systemic side effects reported till date.[26-28] Unlike the other methods, finite element analysis (FEA) is a non-invasive method wherein the various orthodontic treatment procedures pursued can be simulated and the efficiency of treatment can be easily evaluated.[29,30] The aim of the present in-vitro study was to evaluate tooth displacement and assess stress distribution patterns and changes in the centre of resistance (CRes) in TADs-assisted individual canine retraction cases with and without MOP using the FEA model.

Materials and Methods

The in-vitro comparative study was approved by the Scientific Review Board and Institutional Ethics Committee via. Letter of approval number ADCH/IEC/01-41-2023 The study was conducted in the Department of Orthodontics and Dentofacial Orthopaedics in collaboration with the AnaMacDesign Pvt. Ltd., Gurugram, Haryana, India.

A three-dimensional (3-D) solid model of maxilla was created [Figure 1] to investigate the reaction of the maxillary bone to stresses generated by the applied orthodontic retraction forces as well as to study the effect of MOP on TADs-assisted individual canine retraction cases. The study also evaluated tooth displacement and assessed stress distribution patterns [Figures 2a,b and 3a,b] and changes in the CRes of canine [Figures 4a,b and 5a,b] with and without MOP using the FEA model. The 3-D model of the maxilla was created using Autodesk Inventor and Fusion 360 computer-aided design (CAD), computer-aided manufacturing (CAM) and computer-aided engineering (CAE) software programs with Autodesk Inventor as a CAD platform. Autodesk Fusion 360 is a joint software program combining the CAD platform with CAM and CAE platforms to offer an all-in-one solution with the standardised measurements derived from Nelson SJ's Wheeler's Dental Anatomy, Physiology, and Occlusion (9th ed.).[3] Also, a uniform thickness of 0.25mm was taken when building the periodontal ligament, while the alveolar bone was constructed 1mm away from and along the cementoenamel junction (CEJ) and the thicknesses of the buccal and palatal cortical plates were approximated to 1.10-1.27mm and 2mm respectively, in accordance with the observations made in the systematic review and meta-analysis published by Alfailany et *al*.,[4] on accelerating orthodontic tooth movements. Furthermore, using the Autodesk Inventor and Fusion 360 software programs, the brackets were created in accordance with the MBT-0.022 inches slot prescription for the maxillary arch. The MBT bracket system has been the mainstay in the practice of orthodontics since its inception in the year 1993 by McLaughlin, Bennett and Trevisi.[32] A maxillary model was simulated similar to a case of bimaxillary protrusion where removal of the first premolars was done on both right and left sides of the maxilla with one side of maxilla from the central incisor till the second molar taken as the experimental side (protocol I), while the other side acted as the control side (protocol II).

The fixed orthodontic appliance model was created with the required brackets and molar bands. The model was designed with a full strap-up with an MBT-0.022 inches slot prescription except for the canine, while an auxiliary vertical slot bracket was

designed for the canine alone [American Orthodontics (AO)] which differed from the conventional canine bracket. A molar band measuring 0.005-0.006 inches in thickness and 0.18-0.20 inches in width with distally facing hook and with triple buccal tubes was constructed. In the maxillary model, a transpalatal arch made of 0.036 inches/19-gauge stainless steel wires was built at a height of roughly 2mm from the palatal mucosa. The whole maxillary model was divided into one anterior (from right lateral incisor to left lateral incisor) and two posterior (from second premolar to second molar) segments, while under the arch wire, figure of eight ligations were simulated in both the anterior and posteriors segments. The bracket slot was passively inserted with a rectangular stainless-steel wire measuring 0.46 mm x 0.64 mm (0.019 inches x 0.025 inches), while a serpentine hook made from 0.016 x 0.016 inches stainless steel wire was, then, inserted into the vertical slot of the canine bracket so that the applied force was close to the CRes of the canine. Following this, a TAD measuring 1.5mm x 9mm was simulated in the interradicular region between the second premolar and first molar on the buccal aspect of both sides of the maxilla, while mini-implants were placed approximately 5mm from the alveolar bone crest. Nickel-titanium (NiTi) closed coil springs of 6 mm length, 1 mm diameter and 0.010-inch thickness were placed from the TADs to serpentine hooks on both sides of the maxilla, while this design was used on both the experimental and control sides of the maxilla. In the end, six MOPs, each being 3mm in depth and 1.5mm in diameter, were created on the experimental side of the maxilla with three MOPs each created at distances of 3mm, 9mm and 12mm respectively from the crest of the alveolar bone on both the mesial as well as the distal aspects of the maxillary canine.

An FE mesh was created based on the generated FEA model and node to node connections were made between the NiTi closed coil springs, mini-implants, brackets, teeth, periodontal ligament and the adjoining alveolar bone. The goal of this simulation was to replicate and compare a clinical situation in which the NiTi closed coil springs used the mini-implants as anchorage units to exert a force equivalent to 1.47 Newton (1.47 N) on the canine under the influence of six MOPs on one side as against without influence of MOPs. Both the load and boundary conditions were specified, while any additional boundary condition inputs provided were incorporated into the generated FEA model. The material properties were designated based on the information gathered from the previous studies [Table 1]. The meshing was accomplished using Altair HyperMesh FEA analysis software [Altair Engineering Inc., Troy, Michigan (MI), USA], while further analysis was performed with the help of Ansys Engineering Simulation and 3-D Design Software [Atlanta, Georgia (GA), USA].

For a precise pre-processing (meshing), FE modeling was performed with appropriate element types and sizes. Appropriate material properties were assigned to improve the accuracy of the results and strict element quality parameters were followed. For structural analysis, the FE model was solved, while the stresses and the stress flow in each component were plotted using precise graphic and tabular depictions. The variable(s) assessed included maximum canine displacement (x 10^{-5} mm) in all three axes including the x-, y- and z-axes on both sides of the maxilla with and without MOP; maximum principal stresses (in MPa) generated in canine tooth region on both sides of the maxilla with and without MOP; von Mises stresses (in MPa) generated in the brackets as well as in the periodontal ligament and adjacent alveolar bone (both cancellous [Figure 2a,b] as well as cortical [Figure 3a,b] bone) and in the canine tooth region on both sides of the maxilla with and without MOP and changes in the centre of resistance (CRes) for the canine [Figures 4a,b and 5a,b] on both sides of the maxilla with and without MOP before and after applying load to the canine.

RESULTS

The properties of the materials used in the present FEA model-based study are depicted in Table 1, while Table 2 presents the maximum tooth displacement (x 10^{-5} mm) in all three axes including the x-, y- and z-axes on both sides of the maxilla with and without MOP wherein higher maximum tooth displacement values (x 10^{-5} mm) were recorded on the experimental side (protocol I) along all three axes (1.124 x 10^{-5} mm along x-axis, 2.563 x 10^{-5} mm along y-axis and 0.836 x 10^{-5} mm along z-axis respectively) than when compared to the other side which acted as the control side (protocol II) (-10.808 x 10^{-5} mm along x-axis, 2.543 x 10^{-5} mm along y-axis and 0.808 x 10^{-5} mm along z-axis, respectively).

Table 1: Material properties used in the study

Material(s)	Young's modulus (E=σ/ε) (in Gpa)	Poisson's ratio (v)	Specific Density(in g/cm^2)
Teeth	20	0.30	2.02
Cortical bone	14.7	0.30	1.85
Cancellous bone	1.37	0.26	1.85
Periodontal ligament	6.89x10^{-5}	0.45	1.00
Stainless steel	200	0.29	-
Titanium	114	0.34	-
Nickel-titanium (NiTi)	36	0.33	-

E=σ/ε- Young's modulus (E); Stress (σ) (sigma); Strain (ε) (epsilon); GPa-Gigapascals [the fundamental SI unit (the International System of Units) for Young's modulus (E)]

An important finding in this was the change in the position of CRes of canine which was significantly higher on the experimental side (protocol I) than that recorded on the control side (protocol II) [the CRes shifted 0.6mm occlusally on the experimental side using MOP (protocol I) than on the control side without MOP (protocol II)].

Table 3 shows the maximum principal stresses and Von Mises stresses (in MPa) generated in the periodontal ligament and adjacent alveolar bone (both cancellous as well as cortical bone) and in the canine tooth region on both sides of the maxilla with and without MOP revealing higher maximum principal stresses (0.037 MPa) and von Mises stresses (0.000076 MPa, 0.108 MPa, 0.447 MPa and 0.251 MPa in the periodontal ligament, cancellous bone, cortical bone and in the canine respectively) on the control side (protocol II) as compared to the values which were recorded on the experimental side (protocol I)

Table 2: Maximum tooth displacement ($x10^{-5}$mm) in all three axes including the x-, y- and z-axes on both sides of the maxilla with and without MOP

Side(s)	Total tooth displacement ($x10^{-5}$mm) in x-, y- and z-axes	Along x-axis (Near C_{Res})	Along y-axis (Near CEJ)	Along z-axis (Near root tip)
Control	16.359	-10.808	2.543	0.808
Experimental	16.449	1.124	2.563	0.836

Table 3: Von Mises stresses and maximum principal stresses (in MPa) generated in the periodontal ligament and adjacent alveolar bone (both cancellous as well as cortical bone) and in canine on both sides of the maxilla with and without MOP

Side(s)	Periodontal ligament (von Mises stress)	Cancellous bone (von Mises stress)	Cortical bone (vonMises stress)	Tooth (von Mises stress)	Tooth (Maximum principal stress)
Control	0.000076	0.108	0.447	0.251	0.037
Experimental	0.000064	0.106	0.399	0.250	0.030

Table 4: Comparison of maximum tooth displacement ($x10^{-5}$mm) in all three axes including the x-, y- and z-axes and von Mises stresses and maximum principal stresses (in MPa) generated in the periodontal ligament and adjacent alveolar bone (both cancellous as well as cortical bone) and in canine on both sides of the maxilla with and without MOP

Variable(s)	Side(s)	
	Control	Experimental
Maximum tooth displacement ($x10^{-5}$mm)		
Total tooth displacement ($x10^{-5}$mm) in x-, y- and z-axes	16.359	16.449
Along x-axis (Near C_{Res})	-10.808	1.124
Along y-axis (Near CEJ)	2.543	2.563
Along z-axis (Near root tip)	0.808	0.836
Von Mises stresses and maximum principal stresses (in MPa) generated in the periodontal ligament and adjacent alveolar bone (both cancellous as well as cortical bone) and in canine		
Periodontal ligament (von Mises stress)	0.000076	0.000064
Cancellous bone (von Mises stress)	0.108	0.106
Cortical bone (von Mises stress)	0.447	0.399
Tooth (von Mises stress)	0.251	0.250
Tooth (Maximum principal stress)	0.037	0.030

with the recorded mean values of 0.030 MPa for the maximum principal stresses and 0.000064 MPa, 0.106 MPa, 0.399 MPa and 0.250 MPa for the von Mises stresses generated in the periodontal ligament, cancellous and cortical bone and in the canine respectively. Table 4 presents the summary of the maximum tooth displacement (x 10^{-5} mm) observed along the x-, y- and z-axes and the maximum principal stresses and von Mises stresses (in MPa) generated in the periodontal ligament and adjacent alveolar bone (both cancellous and cortical bone) and in the canine tooth region on both sides of the maxilla with and without MOP.

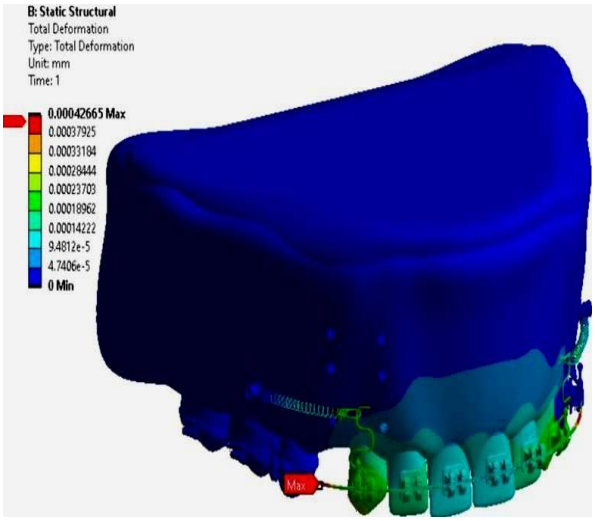


Figure 1: Three-dimensional (3-D) solid model of maxilla used in the study, created with the help of Autodesk Inventor and Fusion 360 computer-aided design (CAD), computer-aided manufacturing (CAM) and computer-aided engineering (CAE) software programs

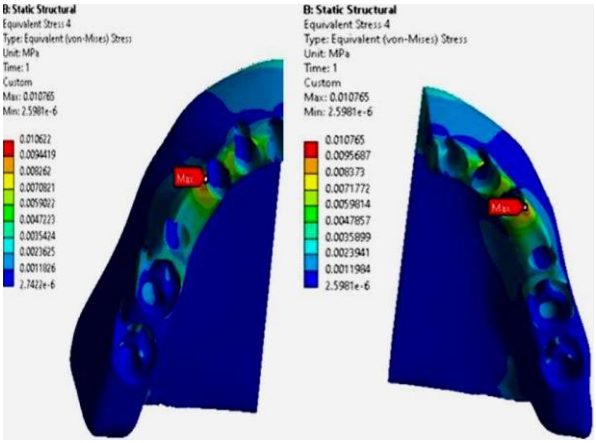


Figure 2a,b: Von Mises stresses (in MPa) generated in the adjacent alveolar bone (cancellous bone) on both sides of maxilla- Left side: a) with, and Right side: b) without micro-osteoperforation (MOP)

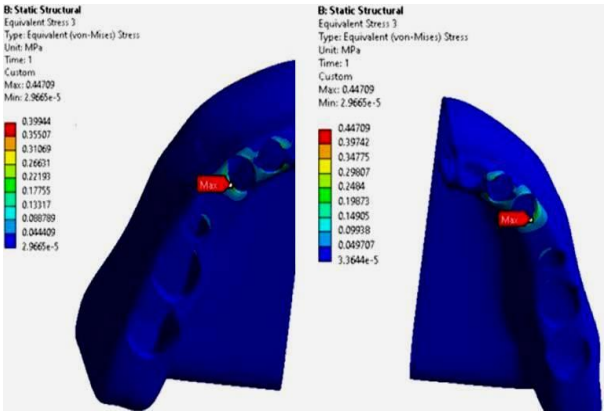


Figure 3a,b: von Mises stresses (in MPa) generated in the adjacent alveolar bone (cortical bone) on both sides of maxilla- Left side: a) with, and Right side: b) without micro-osteoperforation (MOP)

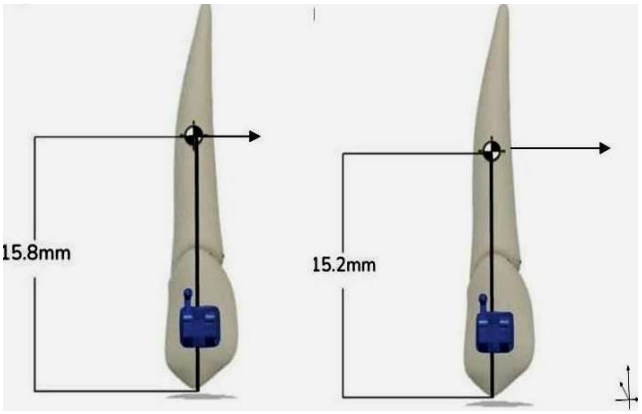


Figure 4a,b: Change in center of resistance (CRes) in a temporary anchorage device (TAD)-assisted individual canine retraction case- Left side: a) before, and Right side: b) after load application equivalent to a force of 1.47 Newton (1.47 N) on experimental side with micro-osteoperforation (MOP) (protocol I)

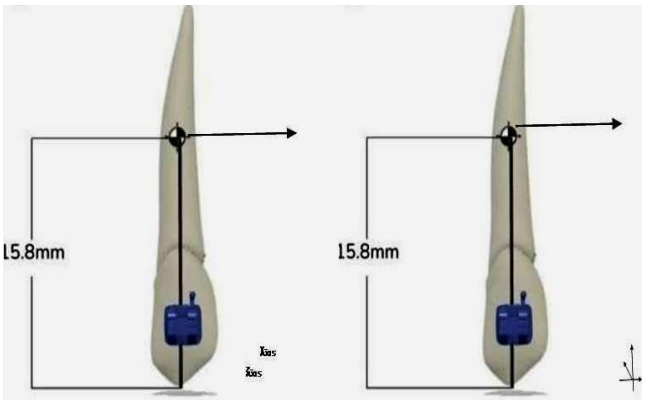


Figure 5a,b: Change in center of resistance (CRes) in the same case- Left side: a) before, and Right side: b) after load application equivalent to a force of 1.47 Newton (1.47 N) on the control side without micro-osteoperforation (MOP) (protocol II).

Discussion

The biological process of orthodontic tooth movement is dictated by the response of the periodontal tissues to the biomechanical forces applied. It is also a process in which the application of a mechanical force causes alveolar bone to resorb under pressure and deposit under tension. In this context, the orthodontic force applied constitutes a complex, 3-D system that is challenging to assess under the actual clinical circumstances and it is crucial to the entire biomechanical process of tooth movement.[14,15] In terms of orthodontic tooth movement, orthodontically guided canine retraction can be achieved by many techniques, while the most important side effect of individual canine retraction is the distal tipping of canine when the force is applied. Conversely, maxillary canine retraction encounters greater resistance from the surrounding alveolar bone and periodontium. In addition to this, anchorage loss is also one of the common problems encountered during maxillary canine retraction.[21-25] The introduction of TADs as absolute anchorage systems largely overcame the disadvantagesencountered during individual canine retraction cases using conventional retraction methods.

Furthermore, to shorten the duration of treatment and with the rise of the concept of accelerated orthodontics, MOP is used with the intent to lower resistance to the tooth movement.[26-28] As far as the present study was concerned, a 3-D model of the maxilla was simulated similar to a case of bimaxillary protrusion using the Autodesk Inventor and Fusion 360 CAD/CAM/CAE software programs in accordance with the study conducted by Pacheco *et al*.[33] Using the software programs, the therapeutic extraction spaces of maxillary upper right and left first premolars were also simulated. The right side of the maxillary mesh model from central incisor to second molar was taken as the experimental side (protocol I), while the contralateral side acted as the control side (protocol II).

The components of the fixed orthodontic appliance comprised of stainless-steel metal brackets with MBT-0.022 inches slot prescription except in the canine with molar bands measuring 0.005-0.006 inches in thickness and 0.18-0.20 inches in width with distally facing hook and with triple buccal tubes constructed on them. The bracket slots were passively inserted with a rectangular stainless-steel wire measuring 0.46mm x 0.64mm (0.019 inches x 0.025 inches) incorporated into the maxillary mesh model. Also, a customized canine bracket with an auxiliary vertical slot bracket was simulated using the software programs, while a transpalatal arch made of 0.036 inches/19-gauge stainless steel wires built at a height of 2mm from the palatal mucosa was incorporated into the maxillary model from maxillary right first molar to maxillary left first molar region. A 2mm space between the palatal bar of the transpalatal arch and palatal mucosa was incorporated into the model to mimic the actual clinical settings. The whole maxillary model was divided into one anterior (from right lateral incisor to the left lateral incisor) and two posterior (from second premolar to second molar) segments. A serpentine hook made from 0.016 x 0.016 inches stainless steel wire was then inserted into the vertical slot of the canine bracket so that the applied force was close to the CRes of the canine. The vertical height of the serpentine hook was kept close to 8mm which was determined using the position of CRes of right and left maxillary canine. For individual canine retraction, titanium mini-implants with dimensions of 1.5mm x 9mm were utilized to provide absolute anchorage, while they were incorporated into the simulation in the safe zone for implant placement which is considered to be the interradicular region between second premolar and first molar on the buccal aspect of both sides of the maxilla at a height of 5mm from the crest of the alveolar bone. The position of mini-implants was simulated according to the anatomical map proposed by Poggio *et al*.[11] Nickel-titanium (NiTi) closed coil springs of 6mm length, 1mm diameter and 0.010-inch thickness were placed from the TADs till the serpentine hooks, while this was simulated for achieving individual canine retraction. A net force of 150 grams (1.47 N) was delivered on each side. Furthermore, on the control side, canine retraction was achieved using NiTi closed coil springs with TADs as absolute anchorage systems with serpentine hooks inserted into the auxiliary vertical slot brackets specially designed for the canine, while on the experimental side, six MOPs each being 3mm in depth and 1.5mm in diameter, were created with three MOPs each created at distances of 3mm, 9mm and 12mm respectively from the crest of the alveolar bone, both on the mesial as well as the distal aspects of the maxillary canine in accordance with the principles (of accelerated orthodontics) as laid by Alikhani.[34] After customizing the maxillary mesh model, the material parameters were programmed based on the information gathered from the previous studies. All the values were calibrated according to the computer's algorithm so that the simulation mimicked the real clinical scenario for retraction of canine. The biological values for teeth, cortical and cancellous bone and the periodontal ligament were assigned into the FEA model. The Young's modulus and Poisson's ratio of the tooth were also assigned as 17Gpa and 0.30 respectively in accordance with the study conducted by Gandhi *et al*.[35] Likewise, the Young's modulus and the Poisson's ratio for the cortical and cancellous bone and for the periodontal ligament were assigned values of 14.79Gpa, 1.37Gpa and 6.89 x 10^{-5} mm Gpa, and 0.30, 0.26 and 0.45 respectively in accordance with the study conducted by Sana *et al*.[12] The Young's modulus and Poisson's ratio of the stainless steel wires were assigned values of 200Gpa and 0.29 respectively in accordance with the study conducted by Maruo *et al*.[36] Similarly, the Young's modulus and Poisson's ratio of titanium mini-implants were assigned values of 114Gpa and 0.34 respectively, while similar values for NiTi closed coil springs were set to 36Gpa and 0.33 respectively in accordance with the study conducted by Sana *et al*.[12] The specific densities of teeth, cortical and cancellous bone and periodontal tissue were calibrated as 2.02g/cm2, 1.85g/cm2, 1.85g/cm2 and 1.00g/cm2 respectively in accordance with the study conducted by Gandhi *et al*.[35] An equivalent of 1.47 N of force simulated on experimental and control sides in the model for carrying out canine retraction was also in accordance with the study conducted by Pacheco *et al*.[33] The loads were applied along with the boundary conditions, while canine retraction was simulated on the experimental and control sides simultaneously and displacement compared on either side.

The results obtained in the present study indicated higher maximum tooth displacement values (x 10^{-5} mm) on the experimental side (protocol I) along all three axes (1.124 x 10^{-5} mm along x-axis, 2.563 x 10^{-5} mm along y-axis and 0.836 x 10^{-5} mm along z-axis respectively) than when compared to the other side which acted as the control side (protocol II) (-10.808 x 10^{-5} mm along x-axis, 2.543 x 10^{-5} mm along y-axis and 0.808 x 10^{-5} mm along z-axis, respectively). Also, an important finding in this was the change in the position of CRes of the canine which was significantly higher on the experimental side (protocol I) than that recorded on the control side (protocol II).

The CRes shifted 0.6mm occlusally on the experimental

side using MOP (protocol I) than the control side without MOP (protocol II). A plausible explanation for this might be because of the impact of MOP on the experimental side because of which the forces applied passed directly through the CRes of canine which in turn resulted in bodily tooth movement in close accordance with the observations made by Alikhani [34]. In this context, even though the serpentine hooks were placed near the CRes of the canine, more resistance was encountered on the control side wherein MOP was not used (protocol II) which resulted in tipping movement at the incisal-thirds of the crown of canine, while on the contrary, MOP used on the experimental side (protocol I) reduced resistance and resulted in a controlled bodily movement (translation) of the canine. Similarly, higher maximum tooth displacement values ($x10^{-5}$mm) were obtained on the experimental side (protocol I) along y-axis (2.563×10^{-5} mm) at cervical-thirds of canine on distal side near the CEJ than when compared to the control side (protocol II) (2.543×10^{-5} mm along y-axis), clinically implying higher extrusive tooth movement on the experimental side (protocol I) than the control side (protocol II). Likewise, higher maximum tooth displacement values ($x\ 10^{-5}$ mm) were obtained on the experimental side (protocol I) in the present study along z-axis (0.836×10^{-5} mm) near the root tip of canine than when compared to the control side (protocol II) ($0.808x10^{-5}$mm along z-axis), though, the difference was not found to be statistically significant.

The results of the present study also indicated higher maximum principal stresses (0.037 MPa) and von Mises stresses (0.000076 MPa, 0.108 MPa, 0.447 MPa and 0.251 MPa in the periodontal ligament, cancellous bone, cortical bone and in the canine respectively) on the control side (protocol II) as compared to the values recorded on the experimental side (protocol I) with the recorded mean values of 0.030 MPa for maximum principal stresses and 0.000064 MPa, 0.106 MPa, 0.399 MPa and 0.250 MPa for the von Mises stresses generated in the periodontal ligament, cancellous and cortical bone and in the canine, respectively, clinically implying an increased chance of the teeth going through external root resorption in the protocols wherein MOP procedures are not performed. Similarly, Ricketts *et al*.[37] stated that cortical bone offers higher resistant to bone remodeling, and this substantiated the findings obtained in the present study wherein higher stress concentration was recorded in the cortical bone on both the experimental and control sides, whereas the application of MOP on experimental side reduced the maximum principal and von Mises stresses in the periodontal ligament and adjacent alveolar bone (both cancellous and cortical bone) in the canine facilitating favorable bone remodeling and thereby increasing the rate of tooth movement with the use of MOP.

A number of factors were taken into account for interpretation of the results in the present FEA-model based study. Firstly, the overall effect of the forces applied for individual canine retraction was evaluated on the experimental and control sides where it was revealed that the experimental side experienced lesser maximum principal and von Mises stresses than the control side, while the principle behind MOP is that the rate of tooth movement increases due to the osteopenia created in the region of MOP. Hence, intentional perforations were made on the surface of cortical bone in order to increase rate of tooth movement in line with findings by Ammar *et al*.,[38] Xue *et al*.,[39] Samgir *et al*.,[40] Dos Santos *et al*.[41] and Mittal *et al*.[42] Similar conclusions were also drawn by Yang *et al*.,[43] Gupta *et al*.,[44] and Ahuja *et al*.[45] where the authors observed enhanced orthodontic tooth movements with procedures such as intentional corticision or corticotomy in select orthodontic cases which was substantiated by the impact of such procedures in interrupting the integrity of bone at the required places and generating the regional acceleratory phenomenon (RAP) to reduce resistance offered by the bone to accomplish desired orthodontic tooth movements.

Also, Alikhani [34] stated that when bone density is reduced, the CRes shifts occlusally towards the direction of the alveolar crest not only increasing the rate of tooth movement, but also bringing bodily movement of the teeth during orthodontic space closures. A similar observation was made in the study conducted by Geramy.[46] In the present study, the position of CRes of canine was observed to be significantly higher on the experimental side than that recorded on the control side [the CRes shifted 0.6mm occlusally on the experimental side using MOP (protocol I) compared to the control side without MOP (protocol II)]. This decrease in the distance between the point of application of orthodontic force and the CRes resulted in a more balanced bodily movement of canine reducing chances of erroneous and unwanted tipping and other tooth movements.

One of the major shortcomings and limitations of the present study was that it was conducted as an in-vitro study design, while any theoretical model of a biological system has some drawbacks, and the results cannot be considered to be exactly replicated in the actual in-vivo conditions. Furthermore, it was presumed that all of the materials used in the study mimicked the actual in-vivo elements, and that their properties were homogenous and isotropic which is contrary to the real clinical situations. The age of the patient, quality of bone, and complexity of the actual clinical environment, can have significant impact on the results obtained. Also, the biological response of the host to the orthodontic forces applied cannot be truly replicated in any FEA model-based study since it only predicts the effects that are expected, which are not entirely realistic.

Conversely, the mediation of orthodontic tooth movements occurs due to the activation of complex inflammatory processes which differ among different hosts, and are largely an independent process; hence, the biological changes occurring at the cellular level cannot be exactly depicted in the FEA model. Also, continuous tooth movement and bone remodeling occurs in a clinical setting, while the reaction of the bone to an initial force application can be different in the

actual in-vivo conditions from what is expected and measured in the FEA model. Additionally, the present study did not take into account stresses generated in the soft tissues, while soft tissues such as the gingiva and the facial muscles may also provide resistance to orthodontic tooth movements which is difficult to assess in any FEA model-based study. Finally, MOP itself, as a minimally invasive technique that triggers an inflammatory response in the alveolar bone of the host accelerates orthodontic tooth movement. It is a type of minor surgical procedure that needs a highly balanced and technique-sensitive approach, and should be performed in an aseptic environment under strict protocols with continuous observation and regular monitoring of the patients.

Conclusion

The results obtained in this study indicated reduced maximum principal and von Mises stresses in the periodontal ligament and adjacent alveolar bone (both cancellous and cortical bone) and in the canine, with an increased rate of tooth movement with the use of MOP. Furthermore, the CRes was observed to shift 0.6mm occlusally on the experimental side using MOP (protocol I) compared to the control side without MOP (protocol II), this resulted in a more balanced bodily movement of the canine reducing chances of erroneous and unwanted tipping and other tooth movements. It can be concluded that MOP significantly reduced resistance to orthodontic tooth movement, thereby considerably reducing the total duration of treatment. However, the present study paves the way for further randomized controlled trials (RCTs) using in-vivo study designs and actual clinical settings with long-term follow-up to further demonstrate efficacy of MOP procedures. Further histological studies are also recommended to assess and study the exact biological changes occurring at the cellular level during orthodontic treatment protocols with and without the use of MOP.

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Conflicts of Interest

There are no conflicts of interest

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