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Finite Element Study to Evaluate the Stress Around Mini-implant during Canine Retraction using Continuous and Interrupted Orthodontic Forces

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Abstract

BACKGROUND: Stress around mini-implant during canine retraction may affect the choice of the type of orthodontic forces that better be used during this dynamic movement. Finite element analysis is a numerical technique, which provides an approximate solution for the applied loads under certain conditions to measure the stress accurately around mini-implant as it is impossible to measure the stress accurately around mini-implant *in vivo*.

AIM: This work aimed to determine the stress distribution around a mini-implant during dynamic canine retraction utilizing continuous and intermittent orthodontic forces and a three-dimensional finite element model.

MATERIALS AND METHODS: A three-dimentional finite element model was established to study stress during canine retraction. The model incorporates a mini-implant, alveolar bone, maxillary teeth, a closed coil spring, and an elastic chain. They were described as being homogeneous, isotropic, and linear elastic. Continuous and interrupted forces were approximated by a NiTi coil spring and an elastic chain, respectively. To retract the canine, a simulated orthodontic force of 1.5N, 2N, and 2.5N were loaded. ANSYS evaluated the value of the stress distribution around the mini-implant, canine, and bone interface (workbench 19).

RESULTS: The present study showed that there was no significant difference between the values of maximum stress around the miniscrew, canine, and bone under different orthodontic loads when a closed coil spring and an elastic chain were evaluated.

CONCLUSION: The stress distribution around a mini-implant during canine retraction was not significantly affected by the amount of the forces or the materials used.

Introduction

Because of their capacity to give absolute anchoring, miniscrews have been used as orthodontic anchorage. Several kinds of titanium miniscrews have recently attracted a great deal of attention, to overcome the problems of conventional anchorage, as titanium screws have gained popularity in orthodontics as an absolute source of anchorage, as they can be loaded immediately, are smaller, are easier to place, can be placed in more varied locations, are more cost effective, and produce better results [1], [2].

As miniscrews do not require patient cooperation, these screws have clinical uses including canine retraction, en masse retraction of all anterior teeth, intrusion of anterior or posterior teeth, and distalization of molars [3].

Clinical success of a miniscrew is primarily dependent on how mechanical stress is distributed from the miniscrew to the surrounding bone.

Mini-implant failure has been attributed largely to infection and secondarily to biomechanical characteristics such as the length, diameter, and insertion angle of the mini-implant into the bone. By understanding the stresses generated along the surfaces of a mini-implant and in the surrounding bone, the design and location of mini-implants can be adjusted, hence reducing the likelihood of failure. The treatment approach for many patients with Class II malocclusion or dentoalveolar protrusion frequently includes excision of the bilateral maxillary first premolars and retraction of the anterior teeth with maximum anchoring.

Three-dimensional finite element analysis (FEA) is a numerical technique for simulating the mechanical process of a real physical system; it is regarded as a realistic and trustworthy method for determining stress, strain, and displacement of dentoalveolar structure [4]. Unlike clinical or animal experiments, this method can be utilized to replicate the orthodontic process with different treatment plans and assess their biomechanical effects without expanding the sample size of patients or animals. FEM enables the analytical application of several force systems at any location and in any direction, as well as the quantitative evaluation of the distribution of these forces throughout the wire and related structures [5].

The purpose of this study was to assess the stress distribution around mini-implant during canine retraction using continuous and interrupted forces, by finite element model.

Materials and Methods

3D finite element model construction

Computed tomography (GE Optima 16/GE Viewer) images of the patient's head (maxilla and maxillary teeth) were taken, scanned, and recorded for the building of a 3D finite element model.

Using spiral computed tomography, the images were acquired in a DICOM (Digital Imaging and Communication in Medicine) data format with a slice thickness of 1.5 mm (CT). The CT was thresholded to distinguish the teeth from the other structures by selecting density using (Software 3 diagnosys 4.2), then any residual bone was segmented. Only one tooth was cut from each tooth in order to separate them as separate objects.

After that, all teeth were recollected utilizing (Plastycad Software) and digital scanning of a plaster cast with a 0.022-in slot stainless steel bracket (open technological optical scanner, Italy). The DICOM data were reconstructed to 3D surface data, digitized into digital imaging, then transformed to a preliminary model. Meshing of all model components to correct topology issues, deletion of brackets, and repetition of steps for brackets as a new part using a commercial computer-aided design program (Solidwork 2016), and import to have finite element model as shown in Figure 1.

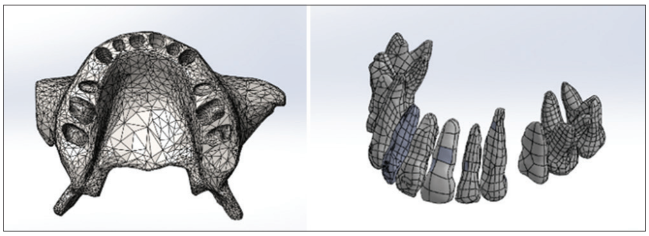


Figure 1: Meshing of maxilla and teeth

The mini-implant was created as a titanium screw with a small head, tapered type, exterior diameter of 1.4 mm, length of 8 mm, and insertion angle of 90° [6], [7]. The geometry of the mini-implant was based on the dimensions and measurements obtained from the study by Singh *et al*., who employed a microscope tool marker with a precision of 10 mm to measure the real dimension of a miniscrew. Figure 2 displays all of the intended miniscrew's dimensions [8].

Continuous and intermittent forces were reproduced, respectively, by a NiTi closed coil spring

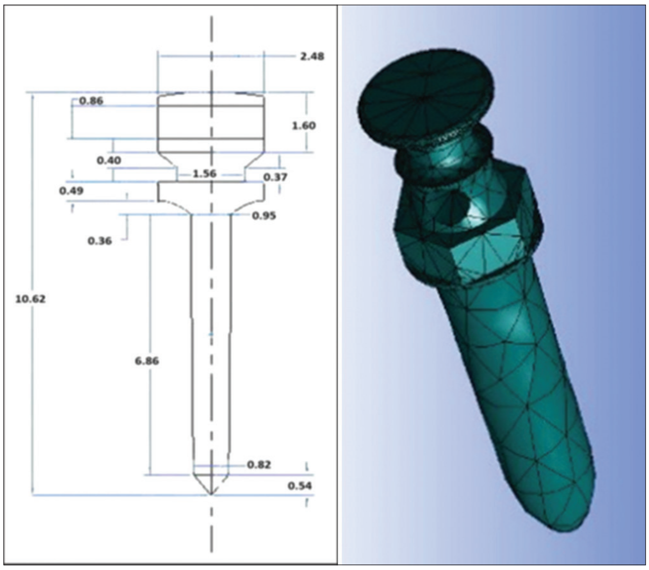


Figure 2: The 3D model of mini-implant

and an elastic chain [9], [10], [11], [12], [13]. The lengths of the coil spring and elastic chain were derived from the dimensions reported in 1993 by Han and Quick [14].

For a more accurate simulation of the movement of canine retraction during orthodontic treatment, a three-dimensional finite element model was developed using computed tomography scans with a slice thickness of 1.5 mm for the following components:

1. The dentition of the maxilla with the first premolars extracted.
2. The dental alveolar bone.
3. A conventional pre-adjusted edgewise bracket with a 0.022-in slot shown in Figure 3.

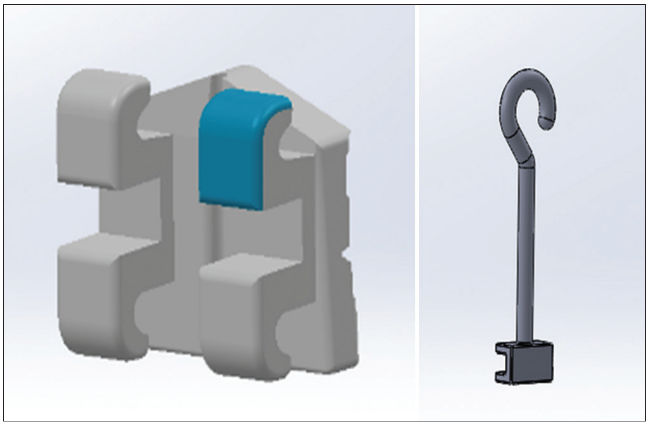


Figure 3: The model of bracket and power arm

4. A stainless steel archwire measuring 0.017 × 0.025 in.
5. A 8 mm-long stainless steel power arm shown in Figure 3 [15], [16].
6. A closed nickel-titanium coil spring [17].
7. The tapered mini-implant was constructed with an exterior diameter of 1.4 mm and a length of 8 mm.

All of these components were subsequently digitalized and transformed into 3D finite element models of the maxilla during canine retraction using the commercial computer-aided design software Solid works 2016 shown in Figure 4.

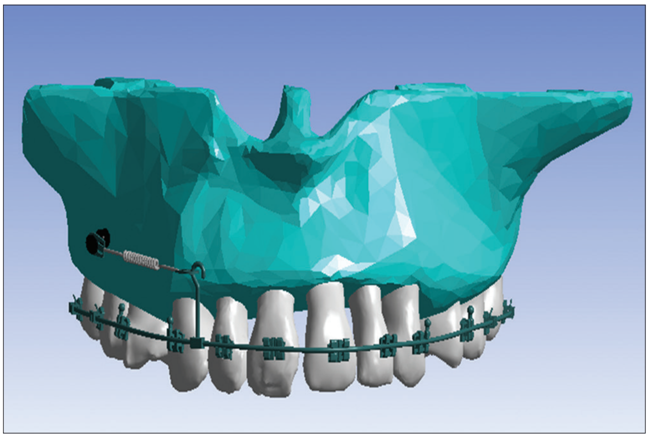


Figure 4: The 3D model of the maxilla with all components

The modules of finite element analysis were defined as homogeneous, isotropic, and linearly elastic substances. The mechanical characteristics of the materials were determined using references from the literature. Table 1 lists the values of elastic modulus and Poisson's ratio that were employed. A number of elements and nodes constitute the 3D finite element model. The total number of nodes and elements is depicted in Table 2. The table displayed the number of model nodes and elements with and without wire, brackets, and miniscrew. The model was tetrahedral element-meshed [8], [18], [19], [20].

Table 1: Material properties used in the model construction

Material	Young's modulus (Mpa)	Possion's ratio
Tooth	2×10^4	0.30
Alveolar bone	2×10^3	0.30
Bracket	2.1×10^5	0.30
Arch wire/hook	2.1×10^5	0.30
Mini-implant	110×10^3	0.35
Elastic chain	100	0.30
Closed coil spring	110×10^3	0.35

Table 2: Approximate numbers of nodes and elements

Item	Number of elements	Number of nodes
Model without wire, brackets, and miniscrew	81,964	142,493
Model with wire, brackets, and miniscrew	124,484	233,398

3D FE model evaluation

The finite element model of the maxilla was loaded into the ANSYS software, which was then utilized to determine the stress using post-processing analysis [21]. As depicted in Figure 5, the stress on the bone element was evaluated using Von Mises equivalent stress.

The model was subjected to simulated orthodontic forces of 1.5N, 2N, and 2.5N, and the stress distribution on the mini-implant, canine, and bone interface was examined [22].

Using the ANASYS software, all variables pertaining to stress distribution and maximum stress were assessed for the design's teeth, mini-implant, and surrounding bone.

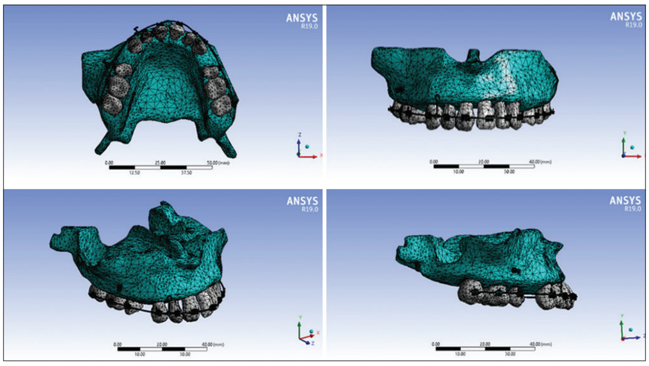


Figure 5: The diagram shows the model using ANSYS software

Results

A color scale will be used to illustrate the maximum stresses for various model components, such as the miniscrew, canine, and bone. The unit for all stress values was the Mega Pascal, which is defined as Newtons per square millimeter.

I-Mini-implant result

When employed with a force of 1.5 N, the NiTi coil spring produced a stress of 25.86 Mpa in the miniscrews, as depicted in Figure 6 and Table 3. At the same level of force, the stress caused by elastic force was 26.98 Mpa.

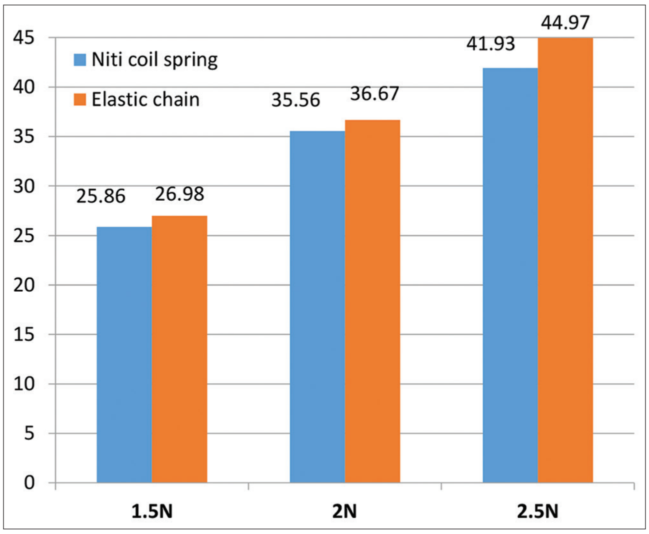
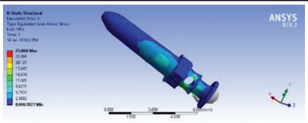
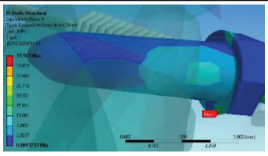
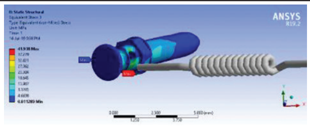
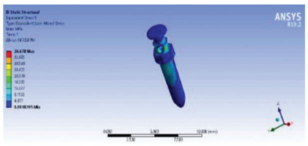
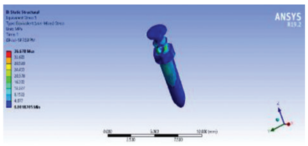
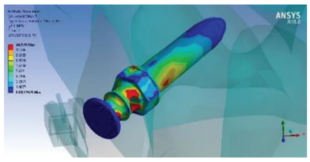


Figure 6: Bar chart shown the maximum stress in miniscrew in both Niti coil spring and elastic chain using different forces

When the force reaches 2N, the NiTi coil spring produces a miniscrew with a pressure of 35.56 Mpa. At the same force level, the stress that resulted in elastic force was 36.67 Mpa.

When the force reaches 2.5N, the NiTi coil spring produces stress of 41.93 Mpa. At the same force level, the stress that resulted in elastic force was 44.97 Mpa.

Table 3: Von mises stress in mini-screw

Orthodontic load	1.5N	2N	2.5N
NiTi coil spring	 25.86	 35.56	 41.93
Elastic Chain	 26.98	 36.67	 44.97

NiTi: Nickel-titanium.

II-Canine result

Figure 7 and Table 4 demonstrate that when utilized with 1.5 N of force, the NiTi coil spring causes a stress of 8.50 MPa in the coronal portion of the canine. The stress resulting in elastic force at the same force level was 9.25 Mpa.

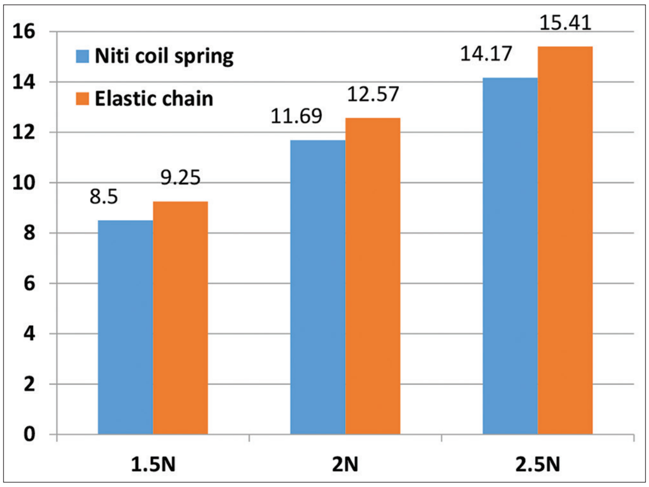


Figure 7: Bar chart shown the maximum stress in canine in both Niti coil spring and elastic chain using different forces

When the force reaches 2N, the NiTi coil spring produces a coronal portion of the canine with a pressure of 11.69 Mpa. At the same force level, the stress that resulted in elastic force was 12.57 Mpa.

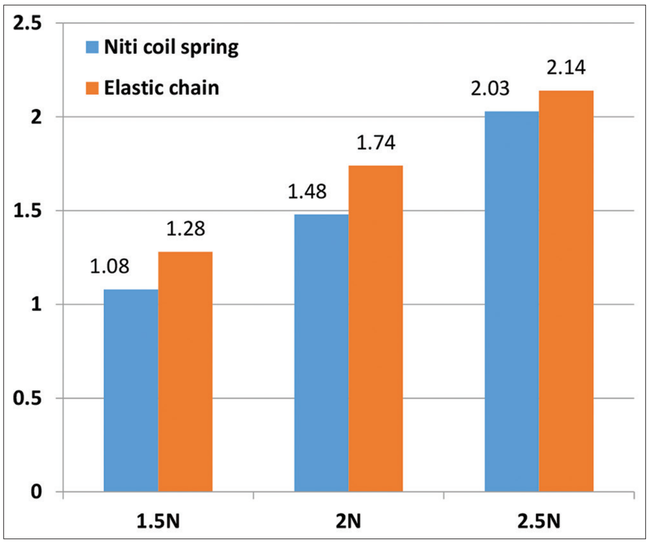


Figure 8: Bar chart shown the maximum stress in bone surrounding miniscrew in both Niti coil spring and elastic chain using different forces

When the force reached 2.5 Newton's, the NiTi coil spring produced a 2.03 MPa bone-encircling miniscrew. At the same force level, the stress that resulted in elastic force was 2.14 Mpa.

When the force reaches 2.5N, the NiTi coil spring produces a coronal portion of the canine with a pressure of 14.17 MPa. The stress resulting in elastic force at the same force level was 15.41 Mpa.

III-Bone result

Figure 8 and Table 5 demonstrate that when utilized with a force of 1.5 N, the NiTi coil spring induces a stress of 1.08 Mpa in the bone around the miniscrew. The stress resulting in elastic force at the same force level was 1.28 Mpa.

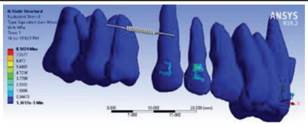
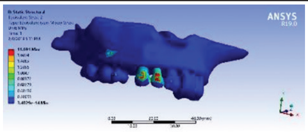
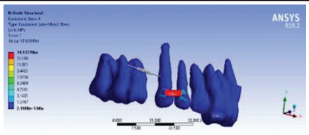
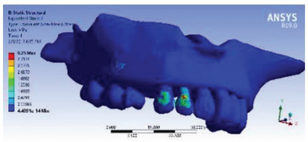
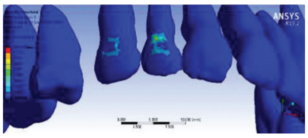
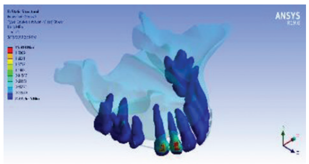
When the force reached 2N, the NiTi coil spring produced a bone-encircling miniscrew with a pressure of 1.48 MPa. At the same force level, the stress that resulted in elastic force was 1.74 Mpa.

Discussion

In this study, a model was created to evaluate the stress distribution around the mini-implant during canine retraction using the finite element approach and continuous and intermittent orthodontic forces.

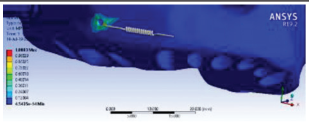
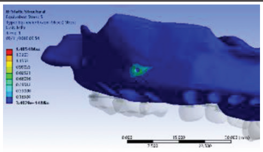
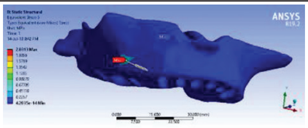
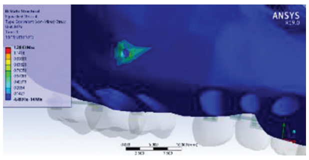
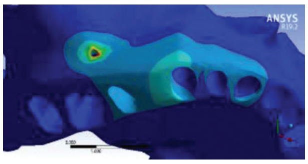
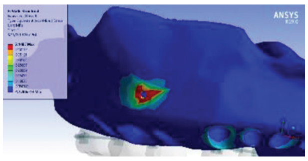
The stress was measured using a finite element analysis with a three-dimensional computer

Table 4: Von Mises stress around canine

Orthodontic load	1.5N	2N	2.5N
NiTi coil spring	 8.50	 11.69	 14.17
Elastic Chain	 9.25	 12.57	 15.41

NiTi: Nickel-titanium.

Table 5: Von Mises stress in bone

Orthodontic load	1.5N	2N	2.5N
NiTi coil spring	 1.08	 1.48	 2.03
Elastic chain	 1.28	 1.74	 2.14

NiTi: Nickel-titanium.

model, which can simulate different circumstances by adjusting the simulation settings [23]. Using the finite element method, this study simulated the orthodontic load for retraction and assessed the stress patterns created at the bone-implant interface.

The finite element approach was a great tool for studying and analyzing biomaterials and human structures, as well as including all relevant design variables in an effort to simulate clinical situations and solve stress-related issues. Using the computer-aided design tool Solidwork, a three-dimensional model of the maxilla (alveolar bone) and the miniscrews were merged to mimic a miniscrew implanted in bone as an orthodontic anchorage unit. These prior research reported the effect and improvement in maxillary protrusion patients treated with miniscrews as opposed to conventional anchorage mechanisms [24], [25], [26], [27], [28], [29], [30].

The reliability of the finite element analysis is dependent on the mesh model; therefore, more nodes would be required for a more precise model. In the present study, the mesh model consists of 81964 elements and 142493 nodes devoid of wire, brackets, and miniscrews, and 124484 elements and 233398 nodes containing wire, brackets, and miniscrews.

In this step, the finite element model of miniscrews, brackets, wire, power arm, and closed coil spring was illustrated using the computer aided design Solidwork program and then transferred to the ANSYS workbench 19.0 program for the finite element analysis, as was previously performed by the Jiang *et al*., methodology [31].

The most often used and recommended orthodontic retraction forces of 1.5N, 2N, and 2.5N were administered from the power arm to the miniscrew anchorage. The load was applied perpendicular to the long axis of the miniscrew's head, by using two distinct retracting mechanisms, a closed coil spring and an elastomeric chain [19], [32], [33], [34], [35].

Based on the findings of Woodall *et al*., the miniscrew utilized in this investigation was inserted perpendicular to the bone surface in an effort to minimize stress in the bone and miniscrew. According to Jasmine *et al*., and Machado *et al*., the use of a 90° insertion angle reduces stress in both the miniscrews and the bone [6], [35], [36], [37].

In accordance with the findings of Byoun *et al*., when the diameter of the miniscrew rose from 1.2 mm to 2.0 mm, the stress in the bone and the miniscrew reduced. According to the results of Gracco *et al*.'s finite element study, the length of the miniscrew with the lowest values of stress is 11 mm, and 9 mm is the ideal length [38], [39].

According to the findings of Duaibis *et al*., the intra-bony length has no effect on cortical bone stress, but the length of the miniscrew head does. It boosted bone stress to its maximum level. In accordance with the majority of studies, increasing diameter reduces bone stress. These findings align with those of Machado *et al*., and Ajami *et al*. [30], [37], [40], [41].

The results of this study are consistent with those of Jasmine *et al*., Gracco *et al*., Ammar *et al*., Singh *et al*., and Ajami *et al*., who reported that the stress was highly concentrated in the head and neck of the mini-implant, despite the fact that the miniscrews used in each of these studies varied in diameter, length, shape, and insertion angle [8], [30], [35], [39], [42].

To investigate the effect of the miniscrew diameter and length on stress distribution, Liu *et al*. reported that increasing the miniscrew diameter decreased bone stress and improved the miniscrew's stability, while the screw length itself was not the true factor, but the exposed length was the most influential factor in the stress [43].

The study result also showed that the stress distribution values of 25.86 Mpa were recorded in the head-and-neck region of the current model when employing a NiTi closed coil spring with an applied force of 1.5 N on the miniscrew. In this model, when a 1.5 N force was applied to a NiTi closed coil spring, the highest stress was seen in the coronal region, around the brackets of the canine and lateral incisors, during retraction, and was reported to be 8.50 Mpa. Similar results were found by Jain *et al*. indicating that the highest stress was seen at bone-miniscrew interface when the retraction was done by NiTi coil spring by stress of 25.889 Mpa [44].

When elastic chain is utilized at the same force level, the stress distribution at the miniscrew is 26.98 Mpa.

The stress produced by a 2N coil spring at the neck of a miniscrew is 35.56 Mpa, while the stress produced by an elastic chain at the same force level is 36.67 Mpa.

The stress at the miniscrew produced by a 2.5N coil spring is 41.93 Mpa. When utilizing an elastic coil spring, the forces would be 44.97 Mpa, and it was found that the stress was substantially localized at the head-and-neck of the miniscrew in all of these instances.

It was discovered that the stress was concentrated in the same area as in the previous studies, and this was in accordance with Suzuki *et al*., who reported the maximum stress in the pin-type miniscrew to be between 268 and 928 MPa, Chang *et al*., who reported 27.31 MPa, and Machado *et al*., who obtained the same results [20], [29], [37].

Changes in the stress distribution pattern may be attributed to a change in the amount of the force, which appeared to have a significant influence in the stress response.

In the canine's coronal region, the application of 1.5N by elastic chain resulted in 9.25 Mpa of pressure. This result was similar to study done by Jain which investigated that stress of 9.63 Mpa between canine region and lateral incisor.

Coil spring of 2N exhibited canine stress of 11.69 Mpa, whereas elastic chain with the same force exhibited canine stress of 12.57 Mpa.

The stress in the coronal portion of a 2.5N coil spring is 14.17 Mpa, although the canine and lateral incisors were reported to have the largest stress distribution when an elastic chain with a force magnitude of 2.5N was used. This region had a stress distribution of 15.41 Mpa [45].

The results showed that stress in the bone surrounding the miniscrew while utilizing a NiTi closed coil spring with a force of 1.5 N was found to be localized in the outer layer of the alveolar bone and began at the compression side with a value of 1.08 Mpa. While utilizing an elastic chain with a 1.5 N force, the bone stress was 1.28 MPa and appeared as a small area on the compression side. This result was similar to study done by Ramesh *et al*. [46].

Table 5 depicts a color map of the model when 2N of force was applied to a coil spring, which revealed 1.48 MPa, and when the same force was applied to an elastic chain, which produced 1.74 MPa. These results correlate well with a study done by Ramesh *et al*. [46].

As seen by the color map, when a 2.5N coil spring is utilized, the stress is 2.03 Mpa, while in Table 5, when a 2.5N elastic chain is employed, the bone stress is 2.14 Mpa.

Conclusion

Within the limitations of this study, the distribution of stress around mini-implant during canine retraction was not significantly different under different orthodontic loads when a closed coil spring and an elastic chain were evaluated.

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