Research Article

A Three-dimensional Finite Element Analysis of Displacement and von Mises Stress on T-loop Spring and Ramus Screw to Evaluate Effective Treatment Modalities during Uprighting of Severely Impacted Mandibular Second Molars

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Abstract

Objectives: The objectives of this study were as follows: (1) To evaluate von Mises stress on mandibular bone with ramus screw and T-loop spring in impacted 40° mandibular second molars (MM2) and (2) to evaluate the displacement and von Mises stress on ramus screw and T-loop spring during uprighting of 40° MM2. **Materials and Methods:** A surface 3D model of the mandibular jaw containing impacted MM2 reconstructed from the cone-beam computed tomography image. To upright the impacted MM2 with ramus screw, a button bonded on distal surface of impacted MM2 and an elastomeric chain was stretched between ramus screw and bondable button. For uprighting impacted MM2 with T-loop spring, the titanium molybdenum alloy wire was adapted to fit passively into the brackets on the anchor teeth and gabled at T to exert an uprighting force on 40° MM2. **Results:** The von Mises stress on the mandibular bone in 40° MM2 with ramus screw was greater compared to the T-loop spring. The displacement and von Mises stress in the ramus screw were greater compared to the T-loop spring during uprighting 40° MM2. **Conclusions:** This finite element analysis revealed that the stress on ramus screw was greater to offer an efficient and innovative possibility for utilizing anchorage to upright impacted 40° MM2.

Keywords: Imapcted manibular second molar, Ramus screw, T-loop spring.

Introduction

Impaction of the mandibular second molars (MM2s) is more commonly unilateral and mesially inclined. Factors that impede the eruption of the MM2 are lack of arch length, abnormal erupting angulation, premature eruption of the mandibular third molar, deviations in the dentition, etc.[1] On the other hand, impacted MM2 develops iatrogenically during orthodontic treatment such as lip bumper or lingual arch therapy, banding, and distalization of MM1.[2] Impacted MM2s may result in the extrusion of opposite teeth, periodontitis, caries, and root resorption of the nearby MM1s.[3] However, these issues might get resolved with orthodontic uprighting treatment modalities. The severely impacted MM2 would be difficult to correct with conventional orthodontics treatment modalities. Extrusion is an expected side effect of cantilever mechanics, because it uses the arch wire as an anchorage unit.[4,5] However, the undesirable side effects on the anchorage unit can be prevented by employing skeletal anchorage. Chang *et al*.[6] developed a stainless steel bone screw with a 2 mm diameter that offers an innovative possibility for utilizing anchorage from extra-alveolar sites, like the mandibular ramus, in response to the constraints of existing conventional orthodontic technique and cotemporary anchorage devices. Finite element analysis (FEA) models which give feedback on the biological responses of bone to biomechanical changes can be easily generated and numerous complementary components to determine the impact on the research subject as well as the adjacent anatomical elements can be simulated.[7] Since the incidence

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of impacted MM2 is relatively low (reported prevalence of 0.06 to 1.36%),there are not many research studies available to justify, of which available treatment options are better. In this study, by comparing two treatment modalities (Ramus screw versus T-loop spring), the best treatment outcome would be evaluated with respect to the severity of impacted MM2.

Materials and Methods

A surface 3D model of the mandibular jaw containing impacted MM2 was reconstructed from the cone-beam computed tomography image with 0.25 mm of cross-sections. The sections was recorded on format digital imaging and communications in medicine and imported into a 3D imaging process and digital reconstruction software package MIMICS 7.10 (Materialise NV, Leuven, Belgium). This geometric surface model in stereolithography format was converted to geometric solid model in initial graphics exchange specification format using modeling software "Solid Edge V19 (Siemens PLM Software, Texas, U.S.);" Hyper Mesh" (version 11, Altair Engineering, Inc. United States of America [USA]) software.

Inclusion criteria

The following criteria were included in the study:

1. A severely impacted MM2 (40° MM2) with enough bone distal to the target tooth for distal movement
2. Alveolar bone level with no impeding third molar for uprighting mechanics.

Exclusion criteria

The following criteria were excluded from the study:

1. Periodontally compromised patient
2. Not sufficient space distal to impacted MM2.

The FEA was performed following these steps

Virtual placement of materials and assignment of material properties

A bone screw was placed 5–8 mm above the occlusal plane, midway between the ascending ramus.[6] A ramus bone screw of 2 × 14 mm SS screw (FavAnchor ™ SAS, India) penetrated the dense cortical bone of the mandible, for uprighting the impacted tooth, a button 3M™ Unitek (3.0 mm) was bonded on distal surface of impacted MM2s, and an elastomeric chain 3M Unitek Alastik Bobbin chain was stretched between ramus screw and bondable button (Figure 1a).

T-loop spring was fabricated with 0.019" × 0.025" titanium molybdenum alloy to upright impacted MM2. T-loop wire was adapted to fit passively into the brackets on the anchor teeth and gabled at T to exert an uprighting force on the molar.[1] (Figure 1b). The mechanical properties of inanimate objects developed using reverse engineering technique are shown in Table 1.

Definition of boundary condition and contact analysis

The boundary condition included a constraint to all degrees of freedom on the bottom and peripheral edge of the bone model to avoid sliding motions. Contact between the screw and surrounding tissue was defined by a non-frictional contact model, which allowed the two contacting surfaces to move independently.[8] The traction force was applied to the center of screw head in downward directions. It was ensured that all contacts were considered fully bonded, which means that the model was considered solid, with no gaps between structures.

Definition of loading conditions

For uprighting the impacted tooth with ramus screw, a button was bonded on distal surface of impacted MM2s, and an elastomeric chain was stretched between ramus screw and bondable button. The distribution of stresses in the surrounding bone and on the screw surface, as well as the displacement of the point of the screw head where the load had been applied, was evaluated using an FEM.

For uprighting the impacted tooth with T-loop spring, the initial length for a T-loop spring was the length of the molar tube + 5 mm, with a 90° gingival bend. After that, the remaining wire was buccally twisted to flare the future loop portion of the spring away from the gingival tissues. The vertical legs which are distal leg and mesial leg of the T-loop segment were spaced 1–2 mm apart with the same height during fabrication. The mesial leg of the T-loop spring bent at a 90° angle approximated at the distal surface of the bracket on the distal of first mandibular molar (MM1) to position the T-loop as far mesially as possible. The MM1, premolar, and canine brackets were fully engaged by the anterior stabilizing spring's design, it is must be passive in all three spatial planes. A stop for the T-loop spring was created immediately anterior to the canine bracket.[9]

Table 1: Mechanical properties of the materials used in modeling

Materials	Youngs modulus (MPa)	Poisson's ratio
Tooth	2.07×10^{4}	0.30
PDL	0.6668	0.49
Bracket	21.4×0.3	0.30
Ramus screw	1.05×10^{5}	0.33
Cortical bone	1.37×10^{4}	0.30
Elastic chain	2.3×10^{3}	0.30
T-loop spring	40000	0.31
Cancellous bone	7.9×10^{3}	0.30

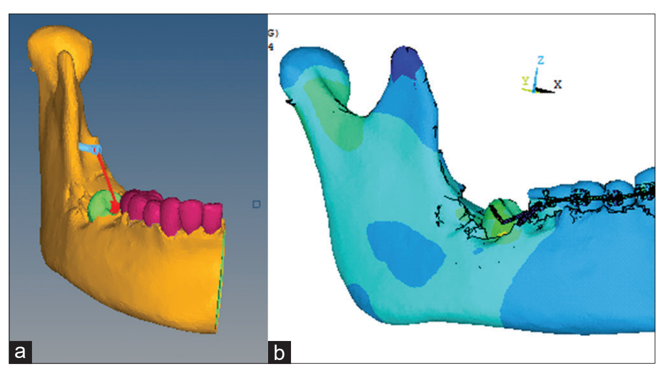


Figure 1: Impacted 40° MM2 model with (a) Ramus screw and (b) T-loop spring

The boundary conditions were set so that the terminal node in the anterior segment was restrained in X- and Y-axis (i.e., it was not able to move and rotate in X- and Y-axis), only the rotation along the Z-axis[10] was allowed, as shown in Figure 2.

Discretization (model meshing)

Modeling should be carefully assessed so as to simplify the model according to its actual needs and without compromising the results. Discretization in FEM means to decompose a complex problem into many simpler problems, whose solution lead to the solution of the complex problem. The total numbers of nodes (or total numbers of elements) comprising the 40° MM2 model were 1,157,628 (765,527). For the discretization of the teeth, the PDL, and the alveolar bone, 4-node tetrahedron element ANSYS software (version 18.1, ANSYS Inc, Southpointe, Pittsburgh USA) was used, and the cortical and cancellous bone and ramus bone screw were all modeled as isotropic, homogeneous, and linear elastic materials. Complete model was constituted of cancellous bone, 1.0 mm cortical bone and 0.25 mm periodontal ligament (Wakabayashi *et al*., 2010),[11] the number of elements and nodes of individual component of the models are shown in Table 2.

Results

Comparison of the von Mises stress on mandibular bone with ramus screw and T-loop spring in 40° MM2

The initial tooth displacement with ramus screw in 40° MM2 shows that the maximum value of displacement was 0.0000172 mm, that was greater compared to T-loop spring in 40° MM2 shows that the maximum value of displacement was 0.0000103 mm.

Table 2: Number of elements and nodes of individual component of the models

Model	Number of elements	Number of nodes
Mandibular impacted second molar	185,885	264,735
PDL	5128	10,469
Bracket	539,526	847,601
Ramus screw	10,607	3034
Cortical bone	94,738	164,534
Elastic chain	15	16
T-loop spring	57	115
Model 40° MM2	765,527	1,157,628

The stress generated with ramus screw in 40° MM2 on the ramus bone and around MM2 was 0.000333 MPa. In 40° MM2 with T-loop spring, the stresses generated on the mandibular bone were 0.0000834 MPa. In summary, the von Mises stress on the mandibular bone with the ramus screw was greater compared to T-loop spring in 40° MM2.

Comparison of the displacement on ramus screw and T-loop spring in initial tooth uprighting of 40° MM2

The maximum value of displacement in ramus screw was 0.000134 mm, recorded in head of implant. In 40°MM2 with T-loop spring, the maximum value of displacement in T-loop spring was 0.0000190 mm, recorded in anterior loop of spring. In summary, the displacement in the ramus screw was greater compared to the T-loop spring.

Comparison of the von Mises on ramus screw and T-loop spring in initial tooth uprighting of 40° MM2

In 40° MM2 with ramus screw, the stress generated on the shaft of bone screw was 0.791135 MPa. In 40° MM2 with T-loop spring, the stress generated on the posterior arm of T-loop spring was 0.047812 MPa. In summary, the von Mises stress in the ramus screw was greater compared to the T-loop spring.

In the present study, the von Mises stress on the mandibular bone with ramus screw was greater compared to the T-loop spring. The displacement and von Mises stress in the ramus screw were greater compared to the T-loop spring during uprighting of 40° MM2.

Discussion

Treatment of impacted 40°MM2 with ramus screw and T-loop spring models was tested in the ANSYS software (version 18.1, ANSYS Inc, Southpointe, Pittsburgh, USA). The uprighting force was applied to the impacted 40°MM2 from which von Mises stress on the mandibular bone was assessed and compared between the ramus screw group and the T-loop spring group. The results obtained are as follows:

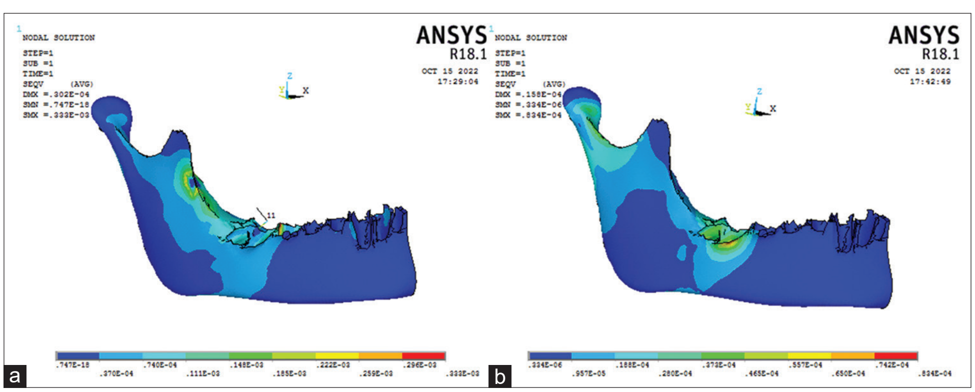


Figure 2: The three-dimensional models, (a) von Mises stress on mandibular bone with ramus screw in 40° MM2 and (b) von Mises stress on mandibular bone with T-loop spring in 40° MM2

Comparison of the von Mises stress on the mandibular bone of impacted MM2 with ramus screw and T-loop spring in 40° MM2

The stress values exceeding the critical threshold of between 50 and 60 MPa have been reported to cause detrimental effects on cortical bone (Sugiura *et al*., 2000). Stress distribution in the cortical bone under all conditions, the largest principal stresses were predicted at the surface of the cortical bone area around the first thread of the bone screw.[12] The stress generated with ramus screw in 40° MM2 on the ramus bone and around MM2 was 0.000333 MPa, whereas the rest of the surface was free of any stresses indicated as dark blue 0.00000000747 MPa at the side coinciding with the direction of orthodontic loading. Maximum stresses in the range of 0.000111–0.000333 MPa indicated as green, yellow, and red. Much less stress was in the range of 0.000000000116–0.0000000194 MPa indicated with dark blue and light blue, respectively (Figure 2a). In 40° MM2 with T-loop spring, the stresses generated on the bone around MM2 were 0.0000834, MPa whereas the rest of the surface was free of any stresses indicated as dark blue 0.000000334 MPa. Maximum stresses in the range of 0.0000280–0.0000834 MPa were indicated as green, yellow, and red. Much less stress was in the range of 0.000000334–0.0000188 MPa indicated with dark blue and light blue, respectively (Figure 2b).

In the comparison of the von Mises stress on the mandibular bone with ramus screw and T-loop spring during uprighting of impacted 40° MM2. Table 3 shows that the von Mises stress on the mandibular bone with the ramus screw was greater compared to T-loop spring in 40° MM2

Loading point displacement

For uprighting the impacted MM2 with ramus screw, the displacement of the point where the load had been applied correlated with the maximum stress induced in both the bone screw and the cortical bone.[13] This displacement was proportional to the angle at which the bone screw was inserted. The largest displacements and stress distribution were predicted with downward traction, the largest von Mises stress were located at the screw neck on the first and/or the second screw thread at the side facing the direction of loading.

Concentrations of maximum stresses had been predicted primarily at both sides perpendicular to the main axis of orthodontic loading (Figures 3a and b). The minimum stresses were generally concentrated at the side coinciding with the direction of orthodontic loading. However, when a bone screw was inserted at an angle of 55°[6] and loaded with force, minimum principal stress concentrations shifted to the opposite side.

Table 3: Comparison of the von Mises stress on mandibular bone with ramus screw and T-loop spring in 40° MM2

Model	40° MM2
Ramus screw	0.000333 MPa
T-loop spring	0.0000834 MPa

For uprighting the impacted MM2 with T-loop spring, it was gabled at T to exert an uprighting force on the impacted MM2 and adapted to fit passively into the brackets on the anchor teeth. The terminal node of the posterior segment was restrained in a similar way to the anterior segment, except that it was free to move along the horizontal leg of the posterior segment, this simulated the movement of the wire sliding through a molar tube of impacted MM2. The loops were activated by the displacement of the distal end by 1 mm in the loops, then bent sharply gingivally to maintain this opening. This activation provides a mesial force on the impacted MM2 that counteracts distal crown tipping while the tooth uprights.[10,11] The maximum displacement on T-loop spring was at the anterior loop of spring, and the minimum displacement was recorded in the end of anterior and posterior leg of the spring (Figures 3c and d).

Comparison of the displacement on ramus screw and T-loop spring in initial tooth uprighting of 40° MM2

In summary, (Figure 3a) shows that the maximum value of displacement on ramus screw was 0.000134 mm, recorded in head of implant, minimum value of displacement was 0.000000634 mm, recorded in the body of implant. (Figure 3c) shows the maximum value of displacement on T-loop spring was 0.0000190 mm, recorded in anterior loop of spring, minimum value of displacement was 0.00000780 mm, recorded in the end of anterior and posterior arm of the spring.

Comparison of the von Mises stress on ramus screw and T-loop spring in initial tooth uprighting of 40° MM2

The stress generated on the shaft of bone screw was 0.791135 MPa indicated as green, yellow, and red, whereas the rest of the surface was free of any stresses 0.087904 MPa indicated with dark blue and light blue, respectively (Figure 3b). The stress generated on the posterior arm of T-loop spring was 0.047812 MPa indicated as green, yellow, and red, whereas the rest of the surface was free of any stresses 0.005312 MPa indicated with dark blue and light blue, respectively (Figure 3d).

The risk of fracture of ramus screw is decreased by increasing the diameter or using a tougher material such as stainless steel, although there have not been any case reports to date suggesting ramus screw fracture, the screw becomes more fracture-prone as its length increases. Chang *et al*., in his study, reported only two of the 37 patients who received ramus screws had inadequate anchorages for molar uprighting due to soft-tissue hyperplasia brought on by poor oral hygiene.

In the comparison of displacement and von Mises stress, on the ramus screw and T-loop spring while uprighting the 40° MM2 (Table 4 and Graph 1) resulted that the displacement and von Mises stress in the ramus screw was greater compared to the T-loop spring.

Clinical application

Extrusion is an expected undesirable side effects on the anchorage unit that can be prevented by employing more complicated mechanics or skeletal anchorage. Kanomi[14] and

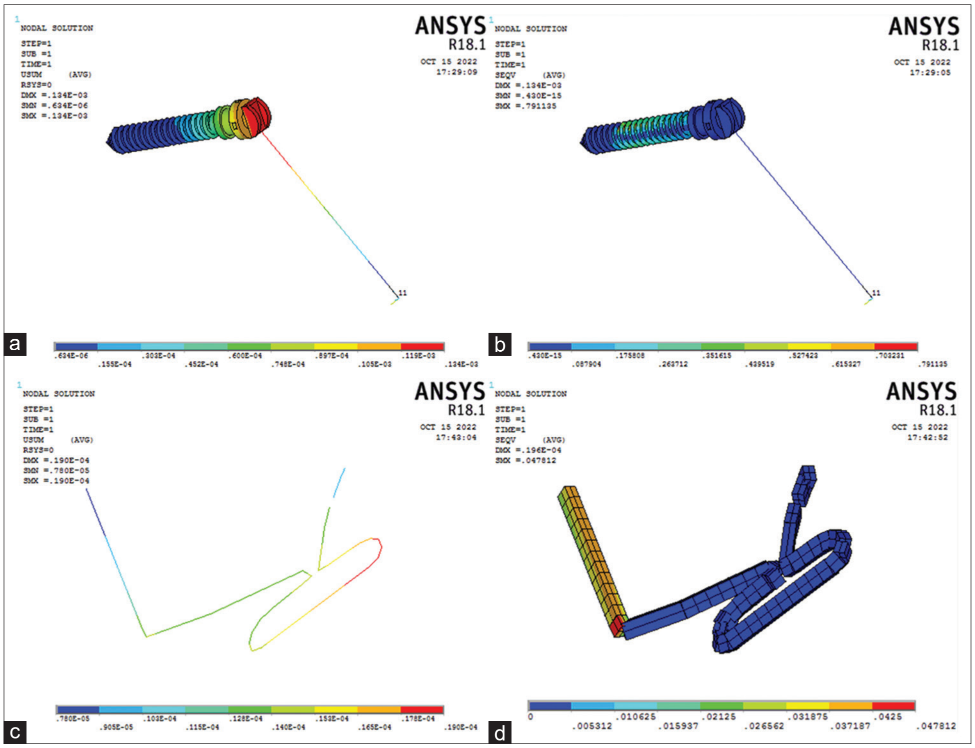
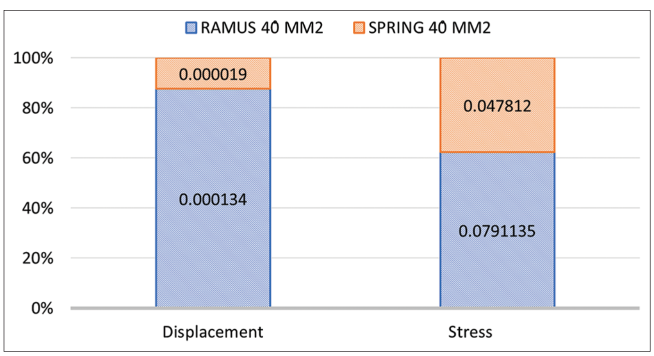


Figure 3: The three-dimensional models of ramus screw and T-loop spring after uprighting 40°MM2, (a) displacement of ramus screw and e-chain, (b) von Mises stresses in ramus screw and e-chain, (c) displacement of T-loop spring, and (d) von Mises stresses in T-loop spring



Graph 1: Graphical plot for comparison of the displacement and von Mises stress on ramus screw and T-loop spring during uprighting of impacted 40° MM2

Table 4: Comparison of the displacement and von Mises stress on ramus screw and T-loop spring during uprighting of impacted 40° MM2

Model	40° MM2
Ramus screw	
Displacement	0.000134 mm
von Mises stress	0.791135 MPa
T-loop spring	
Displacement	0.0000190 mm
von Mises stress	0.047812 MPa

Costa[15] concluded in their study that mini screw was not well suited for complex problems like horizontal impactions, and furthermore, they often had a high failure rate particularly in the posterior mandible. Stainless steel bone screw approach was found to be predictable and effective in the study by Chang *et al*. on 40 horizontally impacted molars that were uprighted with ramus screws. In addition, the study found that the average duration for uprighting the molar was at most 4 months.[16] Lin, in 2011, concluded that the most dependable and efficient procedure involved surgically exposing the deeply impacted molars and pulling them upright with traction using a ramus screw.[17] The anterior ramus of the jaw is the optimal place for an anchorage screw from a biomechanical standpoint.

Limitations of the study

Theoretically, in practice, it is difficult to control and assess the precise force applied to upright the impacted tooth. In the present study, the focus was on the efficiency of uprighting the severely impacted MM2 using ramus bone screw and T-loop springs. The challenges of imitating biological structures for the accuracy of FEA include irregular anatomy, non-elastic, anisotropic, heterogeneous behavior, boundary condition, shape, and size of biological materials, as well as dynamic contact analysis. Comparison between the result of optimal force magnitude from the previous clinical case studies and this static FE analysis is difficult, because the difference in initial angulation and position of impacted molar, force direction, and biological variation such as root morphology, periodontal status, and root surface area. These factors affect PDL stress distribution and optimal force magnitude.

Summary and Conclusions

The von Mises stress on the mandibular bone with ramus screw was greater compared to the T-loop spring. The displacement and von Mises stress in the ramus screw were greater compared to the T-loop spring during uprighting 40° MM2. Additional dynamic finite element studies are needed to stimulate treatment mechanics with the various angulation of impacted MM2. Hence, in cases while application of single-uprighting-force mechanics for uprighting impacted MM2, the clinicians should consider the side effects of the mechanics on MM2, and also the unwanted movement of adjacent anchor teeth. The advancement of ramus screws offers an innovative possibility to address the mechanics in a better way, and utilizing anchorage for efficient uprighting of profoundly impacted and horizontally impacted MM2, which was previously thought to be impossible.

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