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Original Research Article

A comparative evaluation of the displacement and stress distribution of Kilroy spring, ballista spring and temporary anchorage devices during traction of palatally impacted canine using a 3 dimensional finite element analysis

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A B S T R A C T

The above study comprises a comparative evaluation of the displacement and stress distribution of Kilroy spring, Ballista spring and Temporary anchorage devices during traction of palatally impacted canine using a 3 dimensional finite element analysis. Palatally impacted canine is a common phenomenon occuring in around 8% of individuals. The Finite Element Analysis/Finite Element method (FEA/FEM) is the most intricate and dependable study that significantly revolutionized the world of dentistry and biomechanical research. Stresses and displacements can be precisely located using this type of numerical analysis. The orthodontist can better comprehend the physiological reactions that take place within the dentoalveolar complex because of the quantitative information it gives them.

A Cone Beam Computed Tomography (CBCT)scan of the maxilla was obtained from a patient who reported to the Department of Orthodontics and Dentofacial Orthopaedics after he satisfied the inclusion and exclusion criterion. Finite element 3-D models of Kilroy spring, Ballista spring, Cantilever spring, miniscrew, lingual button, 0.022-inch-slot brackets, 0.019x0.025-inch SS archwire, stainless steel bands with molar tubes were constructed using a three-dimensional computer-aided design program (SolidWorks 2017; Solid Works K.K., Tokyo, Japan). All these components were imported and individually assembled in the ANSYS Software (Version 2021 R2, ANSYS, Canonsburg, Pa) and stress analysis was carried out. On the basis of this study following conclusion were drawn: The maximum amount of impacted canine displacement, with initial simulation, wasobserved with Kilroy spring followed by Ballista spring and miniscrew assisted Cantilever spring and the maximum amount of displacement of adjacent teeth i.e. lateral incisor and 1st premolar is observed with Ballista spring followed by kilroy spring and miniscrew assisted Cantilever spring. Furthurmore stress concentration on the canine is highest in case of ballista spring followed by Kilroy spring and miniscrew assisted Cantilever spring. Over all, miniscrew assisted Cantilever spring can be an efficient treatment option for traction of a palatally impacted canine.

1. Introduction

An impaction is a pathological condition where a tooth is well behind schedule in erupting and there are radiographic or clinical barriers to its eruption.[1]

After the third molar, maxillary canines are the most commonly impacted teeth.[2] About 2% of people are affected by maxillary canine impaction. Also they affect women almost twice as frequently than it affects men. Maxilla is affected twice as more than the mandible. Bilateral maxillary canine impactions affect around 8% of

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individuals.[1] Distribution of impacted maxillary canines is such that one-third are labial and two-thirds are palatal.[3] Numerous causes can contribute to canine impaction. Palatally displaced maxillary canines needs thorough investigation. According to Jacoby's[4] research, labially impacted canines have enough space to erupt in about 17% of the cases only while majority of PIC do not have enough space for eruption. Therefore, it is suggested that arch length deficiency is the main cause of labially impacted canines which is not true for palatally impacted canine. Canine impaction can be multifactorial. It can involve etiological factors like systemic, genetic, or localized.

Localized factors like disparities between tooth size and arch length, failure of root resorption of deciduous canine, shedding of the primary canine before time, dilaceration of the root, variation in the development of the lateral incisor root, ankylosis of the permanent canine, missing maxillary lateral incisor, morphological variations in the size of the lateral incisor root, cyst or neoplasm, iatrogenic factors and idiopathic factors can be responsible for maxillary canine impaction.[5]

Early identification and detection of probable impaction is the ideal strategy for managing impacted maxillary canines. Clinical professionals should think about orthodontic treatment followed by exposing the canine surgically and then applying orthodontic traction force on the PIC to get it into occlusion. It's critical that the orthodontist and oral surgeon communicate properly in this situation since it will enable the employment of the proper surgical and orthodontic treatments.

1.1. *The two most popular procedures for bringing PIC into occlusion are-*

1. During early or late mixed dentition it is possible to expose the canine and allowing it to erupt spontaneously[6,7]
2. Surgically exposing the tooth followed by bonding an attachment on it, and then orthodontic force is used to get the tooth into the arch.[4]

Various techniques have been employed to get the impacted canine into the arch. Some of the springs that have been used in traction of a palatally impacted canine are Ballista spring by Harry Jacoby, Kilroy spring by Bowman and Carano, Cantilever spring by Lindauer and Isaacson, Nickel titanium closed-coil spring by Loring L. Ross, K-9 spring by Varun Kalra etc. Along with this TAD assisted traction can also be done.[8]

A mathematical technique known as the finite element method (FEM) involves computer construction of the physical characteristics and shapes of complicated geometric objects. The Finite Element Analysis/Finite Element method (FEA/FEM) is the most intricate and dependable study that significantly revolutionized the world of dentistry and biomechanical research. Stresses and displacements can be precisely located using this type of numerical analysis. The orthodontist can better comprehend the physiological reactions that take place within the dentoalveolar complex because of the quantitative information it gives them.[9,10]

There are a lot of clinical methods available for disimpaction of a palatally impacted canine but there has been no study conducted in the past to evaluate three commonly used techniques via finite element analysis. Therefore the aim of this study was to evaluate and compare the displacement and stress distribution of Kilroy spring, Ballista spring and Temporary anchorage devices during traction of palatally impacted canine using a 3 dimensional finite element analysis.

2. Materials and Methods

This in-vitro FEM study was approved by the Institutional Ethics Committee (IEC) of Kalinga Institute of Medical Sciences at KIIT Deemed to be University, Bhubaneswar (Ref No: KIIT/KIMS/IEC/637/2021, Dated: 06/03/2021).

A Cone Beam Computed Tomography (CBCT) scan of the maxilla was obtained from a patient who reported to the Department of Orthodontics and Dentofacial Orthopaedics, KIIT Deemed to be University, seeking orthodontic treatment, after taking informed consent, with the following eligibility criteria:

2.1. *Inclusion criteria*

1. Patient with a palatally impacted maxillary canine
2. Patient in the age group of 18-25 years
3. Patient with healthy periodontium
4. Patient with Angle's class I
5. Patient with aligned arch
6. Patient without any skeletal abnormality
7. Patient without Bolton's discrepancy

2.2. *Exclusion criteria*

1. Periodontally compromised patients
2. Patient with previous history of orthodontic treatment
3. Patient below 18 years of age
4. Patient having a gross midine shift
5. Presence of any gross craniofacial deformity

One sample was taken for this study. A Cone Beam Computed Tomography (CBCT) scan was taken of a patient who reported to the Department of Orthodontics and Dentofacial Orthopaedics with Angle's Class I malocclusion, who was indicated for maxillary canine disimpaction with the help of fixed orthodontic treatment, after obtaining informed consent.

CBCT data of a patient in DICOM (Digital Imaging and Communication in Medicine) format was imported to an image processing software for 3D design and modeling–MIMICSTM (Materialise. INC). In this, the anatomical data was extracted and segmented to create accurate 3D models. Tetrahedral FE mesh (1mm tetrahedrons) of the maxilla (including teeth and alveolar bone) was created using Visual-Mesh version 7.0 software (ESI Group, Paris, France). The PDL was modeled with an average of 0.25-mm linear thickness. All the materials, including teeth and alveolar bone were considered homogenous and isotropic. Mechanical properties (Young's Modulus and Poisson's ratio) were determined according to previous studies (Table 1).[11]

Finite element 3-D models of Kilroy spring, Ballista spring, Cantilever spring, mini screw, lingual button, 0.022-inch-slot brackets, 0.019x0.025-inch SS archwire, stainless steel bands with molar tubes were constructed using a three-dimensional computer-aided design program (SolidWorks 2017; SolidWorks K.K., Tokyo, Japan).

All these components were imported and individually assembled in the ANSYS Software (Version 2021 R2, ANSYS, Canonsburg, Pa) and stress analysis was carried out.

3. Appliance Design

3.1. Kilroy spring

It was constructed in a 0.016 inch stainless steel wire and was attached to the lingual button on the palatally impacted canine. It was attached to the main archwire, mesial to lateral incisor on one side and distal to 1^{st} premolar on the other side.

3.2. Ballista spring

It was constructed in a 0.016 inch stainless steel wire and was attached to the lingual button on the palatally impacted canine. It was attached to the main archwire, mesial to lateral incisor on one side and distal to 1^{st} premolar on the other side.

3.3. TAD assisted cantilever spring

Cantilever spring was constructed in 0.016 SS wire and was hooked on the TAD at one end and the other end was attached to the lingual button on palatally impacted canine.

3.4. Force simulation

According to Jacoby H[12]an average spring of 0.016 inch, renders a force of 60-100gms. Hence in our study also we simulated a force of 60gms.

Displacement and stress pattern along with maximum von Mises stress was analyzed for each model. Stress was calculated (MPa) through color contour bands, where different colors represent different stress levels in a deformed state.

4. Results

Table 2 shows the total deformation w.r.t. the maxilla, canine,pdl of canine, lateral incisor and premolar in case of the Kilroy spring model, Ballista spring model and the miniscrew assisted Cantilever spring model respectively. Figures 1, 2 and 3 illustrate the above statement.

Table 3 shows the total stress (von mises stress)w.r.t. the maxilla, canine, pdl of canine, lateral incisor and premolar in case of the Kilroy spring model, Ballista spring model and the miniscrew assisted Cantilever spring model respectively. This is illustrated by Figures 4, 5 and 6.

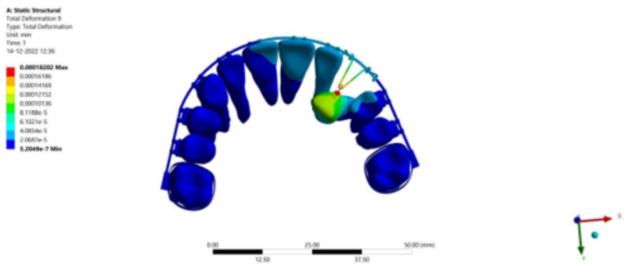

Figure 1: Contour images oftotal deformation with Kilroy spring

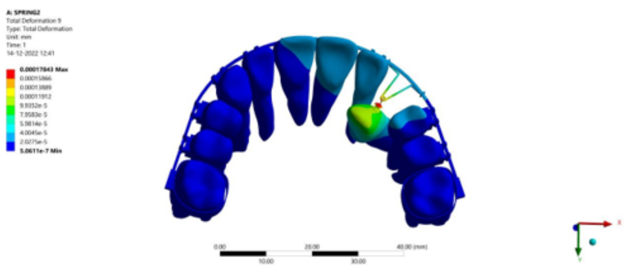

Figure 2: Contour images oftotal deformation with Ballista spring

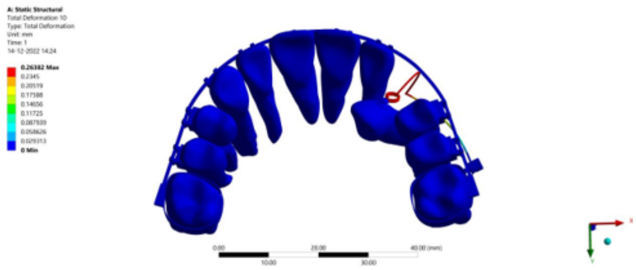

Figure 3: Contour images oftotal deformation with miniscrew assisted Cantilever spring

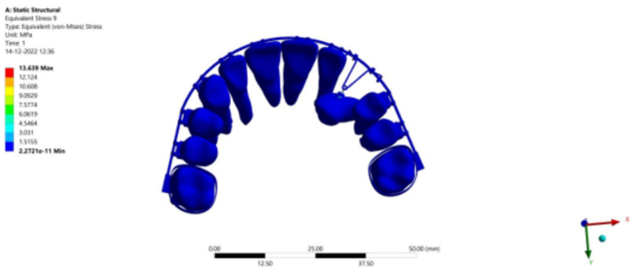

Figure 4: Von Mises stress distribution (Equivalent stress) after application of buccal force with Kilroyspring

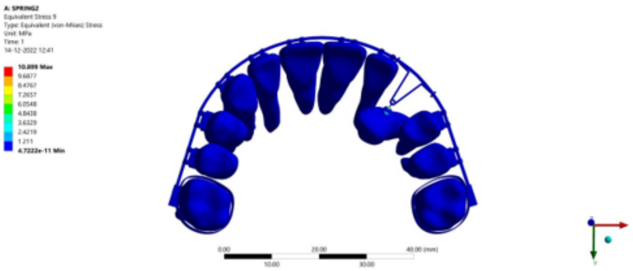

Figure 5: Von Mises stress distribution (Equivalent stress) after application of buccal force with Ballista spring

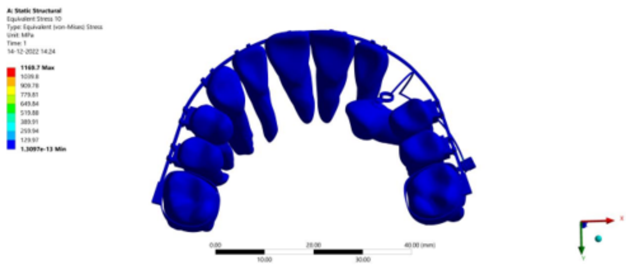

Figure 6: Von Mises stressdistribution (Equivalent stress) after application of buccal force withminiscrew assisted Cantilever spring

Table 1: Young's modulus and Poisson's ratio for various materials

Material	Young's modulus (MPa)	Poisson's ratio
Cancellous bone	7.90 x 103	0.30
Cortical bone	1.37 x 104	0.30
Miniscrew	1.05 x 105	0.33
Tooth	2.07 x 104	0.30
Stainless steel	2.00 x 105	0.30
PDL	50.00	0.49

Table 2: Equivalent stress (von Mises stress) after application of force in case of Kilroy spring, Ballista spring and Mini screwassisted Cantilever spring

Equivalent stress (von Mises stress (mean value)	Kilroy spring	Ballista spring	Miniscrew assisted Cantilever spring
Maxilla	3.37	3.57	2.84
Canine	26.99	27.54	25.92
Canine PDL	0.0007	0.0007	0.0003
Premolar	2.21	2.26	2.12
Lateral Incisor	3.02	3.08	2.66
Miniscrew	-	-	1.19

Table 3: Total deformation after application of forcein case of Kilroy spring, Ballista spring and Mini screw assisted Cantileverspring

Total deformation (mean value)	Kilroy spring	Ballista spring	Miniscrew assisted Cantilever spring
Maxilla	0.006	0.006	0.005
Canine	0.037	0.036	0.034
Canine PDL	0.018	0.010	0.015
Premolar	0.013	0.013	0.012
Lateral Incisor	0.024	0.024	0.020
Miniscrew	-	-	0.003

5. Discussion

Canines are crucial for supporting the entire dentition and helping to create posterior disocclusion during lateral excursions when considering the dentition's functional aspects. Space constraints seem to be the etiological component that causes labial upper canine impactions more frequently. A study found that 85% of PIC have enough space to erupt while that is not the case with labially impacted canines.[4]

It is more appropriate to use orthodontic traction on an impacted canine in situations where there is less significant arch length discrepancies. In order to guide and align the tooth in the arch, the impacted tooth must first be surgically exposed which can be usually accompanied by orthodontic traction through the application of a gentle and gradual force via a bonded attachment.[13]

Various methods are now being employed to pull a palatally impacted canine, including Cantilever springs and elastomeric chain.[14] In their presentation of a cantilever spring for the traction of impacted teeth, Fischer and colleagues highlighted the advantages of low load/deflection rates and fewer activation visits.[15] Kilroy spring, a removable auxiliary spring used by Bowman and Carano for impacted canines, has the advantages of being simple to adjust, exerting constant lateral and vertical stresses, and not requiring patient compliance.[16] Ballista spring by Jacoby, which is a cantilever spring put in the molar tube and first premolar bracket, is one of the most well-known springs for impacted canines. He listed its benefits as easy insertion, continuous force application, and the lack of a more invasive surgical process.[12] In addition to the primary arch wire, Kornhauser introduced the buccal auxiliary spring, which was placed in teeth as a continuous spring. Its benefits are avoided additional laboratory procedures and application of quantifiable pressures.[17]

In our study we used Kilroy spring, Ballista spring and miniscrew assisted Cantilever spring. Kilroy spring does not need particular patient compliance, is simple to insert and regulate, and deliver constant vertical and lateral eruptive forces. The Kilroy II was created for buccally impacted teeth, while the Kilroy I was made for teeth that were impacted palatally. Over the location of an impacted tooth, a constant force module is put onto a rectangular arch wire. The Kilroy spring's vertical loop projects perpendicularly downward from the occlusal plane in the inactive condition. A stainless steel ligature is used to activate the spring. The ligature is passed through the helix and is tied to the attachment bonded on the PIC.[16]

Ballista springs function by continuously building up force as it is twisted along its long axis.The required procedure for the impacted tooth is straightforward and less traumatic. Vertical pressure is applied to the tooth without compressing the impacted tooth against neighbouring roots.This force is easily controlled and manipulated. The aesthetic aspect of the treatment is preserved by not wearing an appliance on the front teeth for a significant portion of the process. It is possible to treat complicated impacted teeth in adult patients.[12]

A length of archwire is used to create a mechanical system called a cantilever spring. The fixed and stable anchorage point is posterior in cases with canine disimpaction. A lever arm attached to the tooth that has to be disimpacted is provided by the free anterior end of the spring. One may regulate the force's orientation, direction, and intensity with the preactivated cantilever arm. In our study we provided this posterior anchorage in form of a miniscrew as they are the most reliable means of anchorage as of now. Any unwanted reactionary force, like intrusion or tipping, is avoided with the use of TADs.[18]

There are currently a lot of clinical case reports and studies available on these springs but any one ideal method for a PIC disimpaction has not been mentioned in the literature. Also it will be not possible to evaluate the different techniques in a clinical case set up due to the presence of confounding factors. Therefore it has become confusing for the orthodontists to select any one method of choice for treating the same.

Additionally, during orthodontic traction of the impacted canine, some side effects such as an extended treatment period, reactionary forces on other teeth and root resorption can manifest. Knowing the correct force's magnitude and direction, as well as the amount of stress and displacement it causes, is crucial for avoiding complications. The present study evaluated the comparative assessment of the above 3 methods using the finite element analysis. In this set up, keeping all the other factors constant we evaluated as to which spring generated the least amount of stress and initial displacement.

As a result of its capacity to provide exact and in-depth information regarding the application of stress on load, FEA is increasingly being applied in dentistry and especially orthodontics. According to Middleton et al., FEA data is more precise than any other experimental technique that are used currently. Additionally, it enables total control of the variables being used while analyzing a homologous sample.[19]In these situations, a computerized three-dimensional geometric model that uses an experiment model enables us to recreate clinical settings without involving actual patients. The purpose of this study was to examine the displacement and von Mises stress distribution on the palatally impacted maxillary canines and the adjacent lateral incisors and first premolars during orthodontic traction using FEA, which was applied in the field of orthodontics.

In a FE study, conducted on Kilroy spring and NiTi closed coil spring in traction of a PIC, it was demonstrated that both methods generated the highest stress on the impacted canine. Also the adjacent teeth suffered more stress in the Kilroy spring set up than the NiTi closed-coil spring set up. In the present study as well the highest stress was found on the impacted canine, in all the 3 set ups. The stress on 1^{st} premolar and lateral incisor was highest in case of Ballista spring followed by Kilroy spring and the least amount of stress was generated in miniscrew assisted Cantilever spring.

In addition to force, canine movement must be regulated biomechanically and directionally since poorly controlled orthodontic traction can put undue stress and strain on the PIC, nearby teeth, and surrounding structures. All the 3 set ups use auxiliary mechanics that deliver slow and continuous force for the traction of the impacted canine. Although the approaches loaded the same starting force magnitude, the biomechanical reactions of the mechanics on the canine and the surrounding teeth were not the same. This is explained by various design biomechanics and how they relate to the canine's center of resistance.

Additionally, differences between the investigations are probably due to differences in the wire's material composition and size, arm length, degree of bending, amount of force, and presence of anchorage devices. The materials used in the current study had identical qualities, therefore we could only analyse how the anchorage system and design mechanics affected the traction of a PIC. However, Zeno et al. found that when a PIC is pulled via the application of buccal force, the PIC suffered greater stress. With the material qualities and design of the mechanics taken into account, we approximated buccal force as a vector from the canine to the point on the wire. As a result, our results are likely to differ from those of the earlier investigations. The displacement values vary because to various design biomechanics and various anchorage configurations.

The ideal force must be used in order to move the teeth as much as possible while causing the least adverse effects.Uncertainty exists over the ideal level of force for canine traction. When pulling on an affected canine, Bishara et al. suggested using light forces up to 60 g. Therefore, it is crucial to remember that the force's magnitude is crucial to preventing undesired repercussions.

The results of this study should be interpreted in light of a number of factors. The setup parameters in a FEM simulation study are essential to achieving a realistic simulation and dependable findings. It is sensitive to the anatomical structures as well as the parameters used to model the materials. Along the root surface, PDL's viscoelasticity and thickness vary.[20]However, as these variations have no impact on the force simulations used in orthodontic treatment,[11,21] PDL was linearly modeled with the same thickness and elasticity along every root. The PDL's mechanical characteristics are highly scrutinized since they play a significant role in orthodontic tooth movement. With this knowledge, the results were interpreted in light of the initial displacements and von Mises stresses of the maxillary teeth in the current investigation. The force applied during traction of a PIC may vary for each patient as a result of individual variances in the effective intervals of PDL stress/strain, but the current results still showed a major significance for clinical orthodontic guidance. Additionally, adopting the identical variables for both procedures will have the least impact on the outcomes because the current study compares the results of the three distinct mechanics.

The limitations of this study were essentially those of a FEM study. Finite Element Method (FEM) allows only initial and momentary effects for force application, as compared to a clinical study where the entire effect of the treatment can be analyzed, while considering the time factor, along with biological elements which are not a part of Finite element analysis. In our study, the time factor was not taken into consideration, and there was a possibility that the mathematical modeling varied from the actual biological condition in a clinical situation. In a clinical setup, the findings may not be similar to the initial response. Owing to the limitations of FEM and anatomical variabilities such as bone stiffness and bone thickness, further clinical evaluation and future studies are warranted to elucidate ideal traction force systems for a PIC.

6. Conclusion

On the basis of his study following conclusion can be drawn:

1. The maximum amount of impacted canine displacement, with initial simulation, was observed with Kilroy spring followed by Ballista spring and miniscrew assisted Cantilever spring.
2. The maximum amount of displacement of adjacent teeth i.e. lateral incisor and 1^{st} premolar is observed with Ballista spring followed by kilroy spring and miniscrew assisted Cantilever spring.
3. Stress concentration on the canine is highest in case of ballista spring followed by Kilroy spring and miniscrew assisted Cantilever spring.
4. Stress concentration on the adjacent teeth is highest in case of ballista spring followed by Kilroy spring and miniscrew assisted Cantilever spring.
5. There is some amount of stress and initial displacement observed around the miniscrew as well.
6. The PDL of canine underwent maximum amount of stress in case of Kilroy spring followed by Ballista spring and miniscrew assisted Cantilever spring.

Over all, miniscrew assisted Cantilever spring can be an efficient treatment option for traction of a palatally impacted canine.

7. Ethics Committee Approval

The ethical clearance for the above study was obtained from Institutional Ethics Committee vide Ref No: KIIT/KIMS/IEC/637/2021

8. Data Availability Statement

The data will be made available on request from the author as and when required on request.

9. Source of Funding

None.

10. Conflict of Interest

The authors do hereby declare that they do not have any competing interests.

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