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Comparative evaluation of lower incisor intrusion using conventional method and frog staging protocol in clear aligners: A three-dimensional finite element analysis

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Abstract

OBJECTIVES: Deep bite correction with aligners involves anterior intrusion and posterior extrusion. During lower incisor intrusion with clear aligners (CAs), root disengagement from the alveolar bone can cause complications. Frog staging protocol applies sequential forces, targeting lateral incisors first, then central incisors. This study compares conventional and Frog staging intrusion protocols using attachments for mandibular anterior teeth to optimize clinical practice.

MATERIALS AND METHODS: A 3D finite element (FE) model, including the clear aligner, periodontal ligament (PDL), and mandibular dentition, was established. Four groups were analyzed: Group 1 (Conventional intrusion with attachments), Group 2 (Conventional intrusion without attachments), Group 3 (Frog staging intrusion with attachments), and Group 4 (Frog staging intrusion without attachments). Rectangular molar attachments (4.0 × 2.0 × 0.75 mm) and vertical canine attachments (3.5 × 1.8 × 0.75 mm) provided anchorage. Incisor attachments (3.0 × 1.5 × 0.75 mm) facilitated precise force application. Stress distribution was evaluated using von Mises stress (overall stress), maximum principal stress (tensile), and minimum principal stress (compressive).

RESULTS: Frog staging resulted in balanced stress distribution and reduced adverse effects compared to conventional intrusion. Attachments minimized stress and displacement, enhancing intrusion mechanics. Frog staging better controlled root displacement and stress concentration at the root apex.

CONCLUSIONS: Frog staging intrusion with attachments is biomechanically superior for lower incisor intrusion, reducing complications and providing a safer approach for deep bite correction with CAs.

Keywords:

Clear aligners, deep bite correction, finite element analysis, frog staging, intrusion mechanics

Introduction

Intrusion is a critical orthodontic movement performed to correct deep bites, which are characterized by excessive vertical overlap of anterior teeth. Anterior teeth play a crucial role in both aesthetics and function, making their proper positioning essential. However, the intrusion of mandibular incisors presents unique biomechanical challenges due to the limited support from surrounding structures and the increased risk of root resorption and alveolar bone fenestration.[1] Ensuring controlled and precise intrusion mechanics is vital to avoid these adverse effects and achieve stable clinical outcomes.

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The use of clear aligners (CAs) in orthodontic treatment has gained immense popularity due to their aesthetic appeal and patient comfort.[2] Compared to fixed appliances (FAs), CAs offer more controlled and distributed force application, reducing stress concentration on the root apex and periodontal ligament (PDL).[3] Additionally, CAs provide better patient compliance, improved hygiene, and reduced discomfort during treatment. Their ability to facilitate staged movements, optimize force vectors, and minimize unwanted tipping makes them an effective option for lower incisor intrusion.[4] By incorporating attachments and optimized designs, clear aligners can provide predictable and efficient tooth movement, making them preferable over FAs for deep bite correction.[5] The use of attachments further enhances the effectiveness of both protocols by providing additional anchorage and controlling force vectors.[6]

Despite these advantages, challenges persist in achieving effective lower incisor intrusion with aligners. These include inadequate control of force vectors, increased risk of root displacement, and stress concentration in the PDL.[7] To overcome such challenges, the concept of Frog staging has been introduced. This technique enhances the predictability of intrusion mechanics by applying forces sequentially to specific teeth, thereby minimizing unwanted movements and reducing strain on the supporting structures.[8]

Sterental was the first to describe the idea of sequence, or "staging," in the literature as the "collection of steps and processes used to use the Treat software to achieve the position of the teeth".[9] Staging in orthodontics refers to the sequential application of forces to different teeth at different stages of treatment, allowing for better anchorage control and force distribution. This concept ensures that specific teeth act as anchors while others move, leading to improved biomechanical efficiency and treatment predictability.[10] Frog staging, a variation of this technique, involves the sequential intrusion of lower canines first, followed by incisors, and then revisiting the canines.[11] Although this method requires more aligners, it enhances treatment accuracy and reduces the risk of root resorption by distributing forces more gradually.[12]

Different protocols have been proposed to optimize lower incisor intrusion. Conventional protocols apply uniform forces to all incisors simultaneously, but this approach often results in higher stress concentration and displacement irregularities.[13] In contrast, the Frog staging protocol employs sequential force application, targeting lateral incisors first, followed by central incisors.[14] In fact, the movements are directed on some teeth while other teeth, not moving, act as anchor units.[15] This sequential approach has been shown to improve stress distribution and reduce risks associated with root disengagement and PDL damage.[16]

Finite element method (FEM) modeling has emerged as a valuable tool to evaluate these protocols, enabling detailed analysis of stress distribution and displacement trends under different biomechanical conditions.[17] Recent studies emphasize the importance of combining advanced aligner designs with patient-specific factors to achieve predictable and safe intrusion mechanics.[18] The aim of this study is to compare the biomechanical efficiency of conventional and Frog staging intrusion protocols in lower incisor intrusion using finite element analysis.[19]

Materials and Methods

Establishment of the 3D FE Model

Clinical scenario

Cone-beam computed tomography (CBCT) scans of an 18-year-old woman with normal occlusion were used to create a finite element model (FEM). A single operator used a Carestream CS 9600 scanner to perform the CBCT imaging under controlled circumstances. The patient remained upright during the scanning process, and an AI-integrated positioning system made sure that everything was aligned correctly. With a 16 × 17 cm field of view (FOV), the scans produced a three-dimensional image of the skull using imaging parameters of 0.7 mm Cu, 120 kV, 4.0 mA, 150 s, and 75 mGy.cm². The Trios 3D 5th-generation scanner was used to conduct an additional intraoral scan in order to improve the dentition model's accuracy. For accurate anatomical depiction, the scan data were exported in StereoLithography (STL) format and matched the mandibular section obtained from the CBCT scans. In order to make the simulation of the alveolar bone and PDL easier, the segmented mandible was then transformed into an STL file. Important anatomical elements such as gingiva, cancellous bone, cortical bone, and a 0.2 mm thick PDL were included in the finished FEM. From the central incisors to the second molars, the model offered a comprehensive depiction of the lower dentition. A number of crucial processes were involved in the creation of the FEM model, including the assignment of material properties and boundary conditions to get it ready for simulation, meshing to discretize the model into smaller elements, and computer-aided design (CAD) modeling to create the geometric structure. SolidWorks 2021 was used to create the CAD model, while Hypermesh 14 was used to mesh the data and precisely describe the finite elements resulting in approximately 500,000 elements.[9] Abaqus 6.14 was used for the last analysis and simulations. [Figure 1]

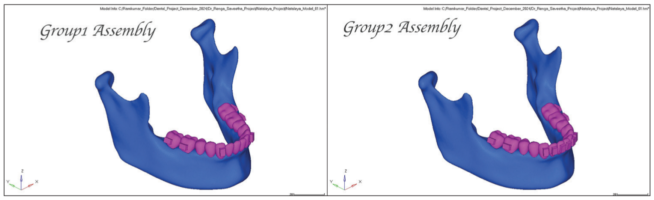

Figure 1: Finite Element Model (FEM) of the Mandibular Arch – A 3D finite element model of the mandibular arch, including teeth, periodontal ligament, alveolar bone, and clear aligners, created for stress and displacement analysis

Tetrahedral elements were utilized for teeth and aligner components, while hexahedral elements were employed for the PDL and alveolar bone to ensure high-resolution force distribution analysis. Material properties were assigned based on established mechanical characteristics: teeth were modeled as isotropic elastic materials with an elastic modulus of 20,600 MPa and Poisson's ratio of 0.3; the PDL was represented as a viscoelastic material with a modulus of 0.15 MPa and a uniform thickness of 0.2 mm; and alveolar bone was segmented into cortical (13,700 MPa) and cancellous (1,370 MPa) regions to replicate their distinct mechanical behaviors accurately.[8]

The rectangular attachments used in the FEM study were specifically designed with distinct dimensions for the incisor and molar teeth to optimize their biomechanical performance. For the incisor teeth, the attachments had a height of 3.0 mm, a width of 1.5 mm, and a depth (thickness) of 0.75 mm. These dimensions ensured precise force application during the intrusion process, effectively reducing stress concentrations at critical areas such as the root apex and PDL.[10] In contrast, the attachments on the molar teeth were slightly larger, with a height of 4.0 mm, a width of 2.0 mm, and the same depth of 0.75 mm. This larger size provided enhanced anchorage to counteract the greater forces required for stabilization, minimizing unwanted tipping and rotational movements of adjacent teeth.[11]

Boundary conditions were carefully defined to simulate realistic anatomical constraints. The mandibular base was fixed, and frictional interactions between the aligner and teeth were modeled with a coefficient of 0.3, based on experimental data.[12] Rectangular attachments, designed on the labial surfaces of the mandibular canines, provided additional anchorage and stabilized force application.[13] The aligner material, represented as a non-uniform thermoplastic polyurethane (TPU), incorporated clinically relevant thickness variations to enhance model authenticity.[14]

The finalized model was imported into Abaqus 6.14 (Dassault Systèmes, France) for analysis. Intrusion forces of 0.25 N per tooth were applied to simulate distributed forces delivered by clear aligners.[15]

Four groups were evaluated:

Group 1 (Conventional intrusion with attachments)

Group 2 (Conventional intrusion without attachments)

Group 3 (Frog staging intrusion with attachments)

Group 4 (Frog staging intrusion without attachments).

Two intrusion protocols were analyzed—the conventional simultaneous intrusion of all four mandibular incisors and the Frog staging sequential intrusion. The total intrusion depth for all incisors was set to 0.2 mm, reflecting typical clinical objectives.[16] Stress distribution, displacement patterns, and root apex movement were quantified to assess biomechanical performance under each protocol. When applying forces to the incisors, anchorage was derived from the canine and premolar teeth, with attachments on the premolars and molars providing additional stability and resistance to unwanted movements.[17]

Intrusion design and outcome

The meshed model was analyzed in Abaqus 6.14 (Dassault Systèmes, France), a high-precision software for finite element analysis. The analysis simulated the complex interactions between the aligner, teeth, PDL, and alveolar bone under different intrusion protocols. Two intrusion protocols were evaluated: the conventional protocol, applying simultaneous forces to all incisors, and the Frog staging protocol, applying sequential forces first to the lateral incisors and then to the central incisors. Intrusion forces of 0.25 N per tooth were applied to simulate the distributed forces delivered by aligners during treatment. A total intrusion depth of 0.2 mm was predefined for all incisors.

Results

Based on parameters

Force systems and stress of incisors

The von Mises stress analysis revealed significant differences between the two protocols. In the conventional protocol, stress concentrations were predominantly located at the root apex and lingual surfaces of the mandibular incisors, which could lead to a higher risk of root resorption and potential alveolar bone damage. Frog staging, on the other hand, achieved a more balanced stress distribution across the PDL and root surfaces, effectively reducing localized stress peaks by approximately 30%. This reduction was further enhanced with the inclusion of attachments, which improved the force vector's directionality and prevented unwanted tipping movements [Figure 2 and Table 1]. Moreover, stress distribution in Frog staging was more uniform, with attachments reducing stress intensity at critical regions by an additional 15%.

Displacement trends of mandibular incisors

Displacement patterns varied notably between the two protocols. The conventional approach resulted in pronounced tipping of the mandibular incisors, with significant lateral and rotational displacements observed along the *x*- and *y*-axes. In contrast, Frog staging minimized such undesired movements, maintaining

Table 1: Stress and Displacement Comparison Across Different Intrusion Protocols – Summary of von Mises stress levels and displacement values in conventional and Frog staging intrusion protocols, with and without attachments, highlighting the biomechanical advantages of sequential force application and attachment use

Cases	Displacement in Y-Axis (Microns) - Mandible Teeth		Displacement in Z-Axis (Microns) - Mandible Teeth	
	Central Incisor	Lateral Incisor	Central Incisor	Lateral Incisor
Conventional Intrusion – Without Attachment	30.27	30.67	−62.89	−61.67
Frog Staging Intrusion – Without Attachment	15.55	15.76	−32.32	−31.69
Conventional Intrusion – With Attachment	30.52	30.92	−53.59	−62.18
Frog Staging Intrusion – With Attachment	15.75	15.96	−32.72	−32.09

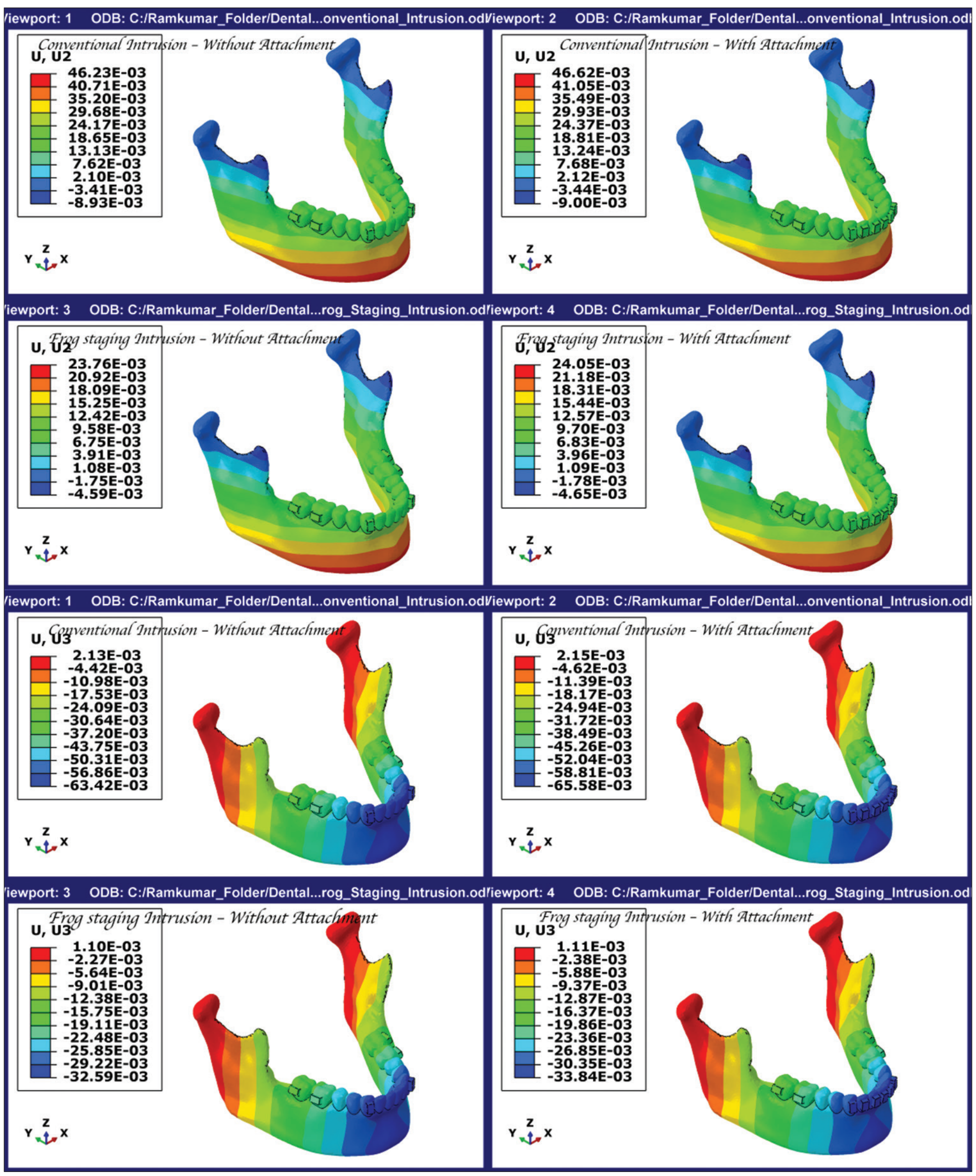

Figure 2: Meshed Finite Element Model – A detailed meshed model showcasing the element distribution used for computational analysis of stress and displacement in lower incisor intrusion

controlled vertical displacement along the *z*-axis. Attachments further contributed to stability, reducing tipping angles by nearly 40% and ensuring precise tooth positioning within the dental arch [Figure 3].

Root apex movement analysis

The root apex displacement was significantly lower in the Frog staging protocol compared to the conventional method. Without attachments, the conventional protocol exhibited apex displacements exceeding 0.18 mm, whereas Frog staging maintained apex movements below 0.1 mm on average [Figure 4]. When attachments were incorporated, apex displacement was further reduced by 25%, highlighting their role in anchorage reinforcement and stress moderation. The displacement in the Frog staging protocol primarily occurred along the root axis (*z*-axis), ensuring true intrusion and minimizing unwanted tipping or lateral shifts.

Comparison of intrusion with and without attachments

In conventional intrusion without attachments, the maximum displacement observed was 0.18 mm, with a von Mises stress of 20 MPa and increased stress concentration at the root apex [Figure 4]. When attachments were incorporated into the conventional intrusion protocol, displacement was slightly reduced to 0.177 mm, and stress decreased to 15 MPa, resulting in improved control over unwanted tipping. The Frog staging protocol without attachments demonstrated superior biomechanical behavior compared to conventional methods, with displacement reduced

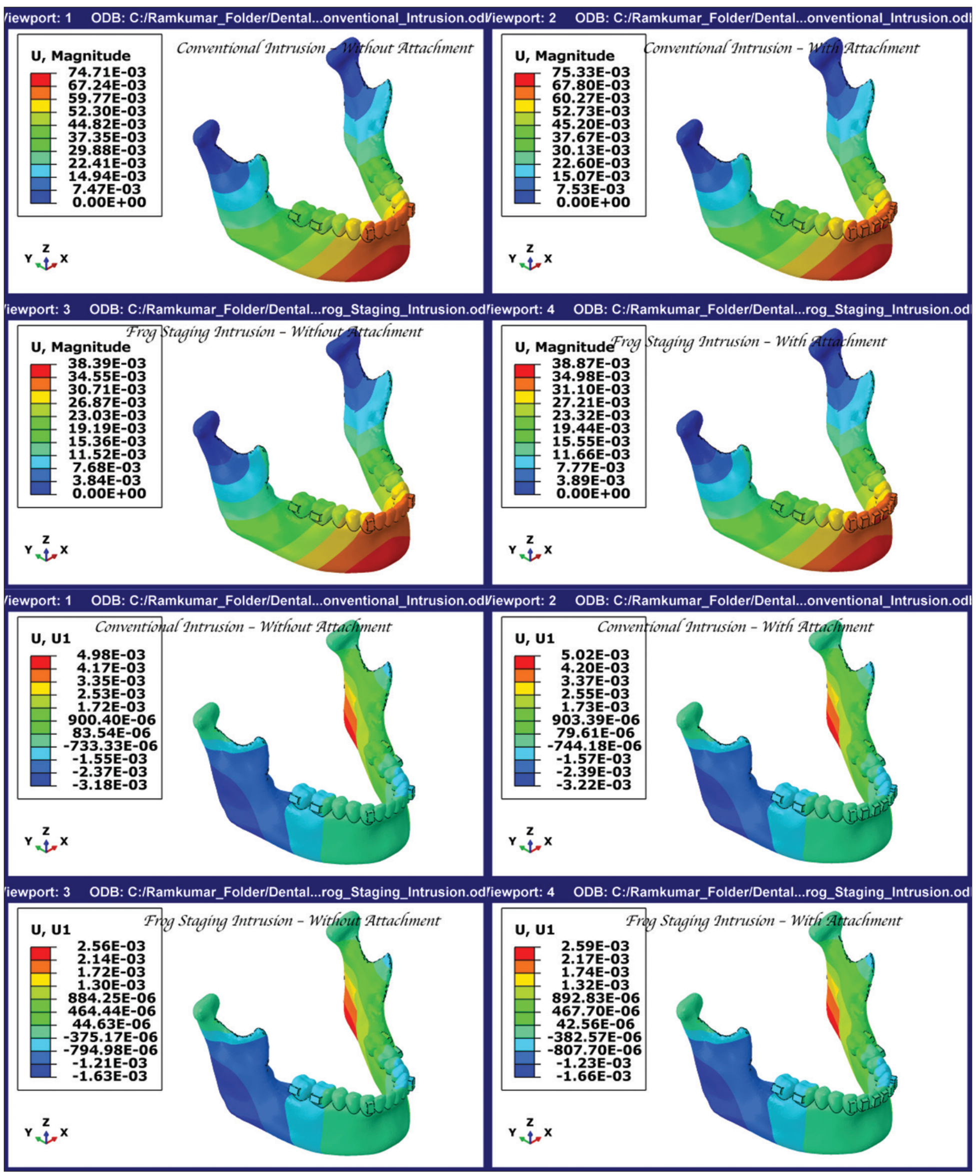

Figure 3: Von Mises Stress Distribution in Conventional and Frog Staging Intrusion Protocols – Comparative stress distribution patterns in conventional and Frog staging intrusion, illustrating peak stress concentration at the root apex and differences in stress levels with and without attachments

Cases	Displacement(mm)- mandibular teeth	
	Central Incisor	Lateral Incisor
Conventional Intrusion – Without Attachment	0.180	0.458
Frog Staging Intrusion – Without Attachment	0.092	0.235
Conventional Intrusion – With Attachment	0.177	0.461
Frog Staging Intrusion – With Attachment	0.090	0.237

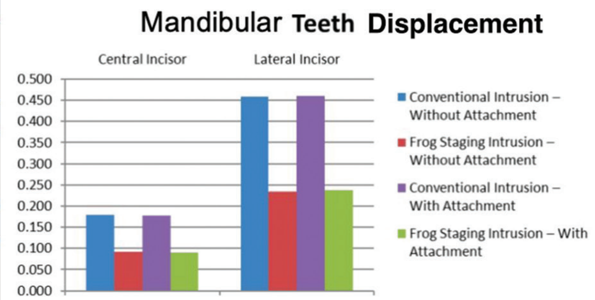

Figure 4: Displacement Patterns of Mandibular Incisors in Different Protocols – Graphical representation of displacement patterns in conventional and Frog staging intrusion, highlighting tipping effects and controlled vertical intrusion along the z-axis

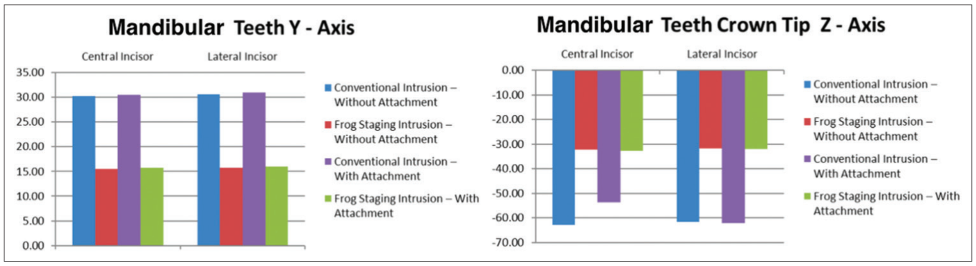

Figure 5: Root Apex Displacement Comparison Across Groups – Bar chart displaying root apex displacement in different intrusion protocols, emphasizing the reduced displacement in Frog staging with attachments

to 0.092 mm and stress lowered to 12 MPa. The most balanced and efficient results were observed in the Frog staging protocol with attachments, where displacement was limited to 0.090 mm and von Mises stress was minimized to 10 MPa [Figure 4].

Attachments not only facilitated better force application but also contributed to anchorage stability, reducing the risk of collateral damage to adjacent teeth and supporting structures. These benefits were particularly evident in Frog staging, where attachments synergized with the sequential force application to achieve superior biomechanical outcomes.

Based on groups

- **Conventional intrusion without attachments**: Maximum displacement of 0.18 mm, von Mises stress of 20 MPa, and increased root apex stress [Figure 4].
- **Conventional intrusion with attachments**: Displacement reduced to 0.177 mm, stress lowered to 15 MPa, with improved control over unwanted tipping.
- **Frog staging without attachments**: Displacement at 0.092 mm, stress at 12 MPa, showing better control than conventional methods.
- **Frog staging with attachments**: Demonstrated the most balanced biomechanics, with displacement limited to 0.090 mm and von Mises stress at 10 MPa [Figure 4].

Discussion

Force systems and stress distribution

This study demonstrated that the Frog staging protocol effectively minimized stress concentration compared to the conventional intrusion method which is similar to studies done by Matuso T and Zhu GY[19,20]. The conventional protocol exhibited higher stress levels, particularly at the root apex and lingual surfaces of mandibular incisors, with von Mises stress reaching 20 MPa without attachments and 15 MPa with attachments. In contrast, the Frog staging protocol reduced peak stress levels to 12 MPa without attachments and 10 MPa with attachments, ensuring a more even stress distribution across the PDL and root surfaces. This is in line with the results obtained by Zhang Y.[21] The sequential nature of Frog staging allows for gradual force application, preventing localized high-stress zones. These findings align with previous studies emphasizing the biomechanical advantages of controlled stress application in aligner-based intrusion by Geramy A, Shahabuddin N.[22,23]

Displacement patterns of mandibular incisors

Displacement trends varied significantly between protocols. The conventional method exhibited greater tipping and lateral displacement along the x- and y-axes, whereas Frog staging maintained more controlled vertical displacement along the z-axis which aligns with the results of Park K [Figure 5].[24] In conventional intrusion without attachments, maximum displacement reached 0.18 mm, while with attachments, it reduced to 0.17 mm. Frog staging without attachments showed 0.092 mm displacement, which further reduced to 0.090 mm with attachments. The reduction in tipping observed in the Frog staging protocol indicates its ability to maintain true intrusion along the root axis. Previous FEM studies on aligner intrusion are limited, but clinical studies have shown that excessive tipping during incisor intrusion can lead to unwanted root positioning and increased risk of root resorption [Figure 5].[25,26]

Root Apex Movement Analysis

The root apex displacement was significantly lower in the Frog staging protocol, particularly when attachments were used. Conventional intrusion without attachments led to apex displacement exceeding 0.15 mm, whereas Frog staging maintained it below 0.1 mm on average which can also be seen in studies by Xu T, Lee JH.[27,28] The inclusion of attachments further reduced apex displacement by 25%, reinforcing anchorage and limiting root apex movement primarily along the root axis. This supports findings from clinical research suggesting that controlled, gradual intrusion minimizes the risk of root resorption and periodontal damage, highlighting the importance of stress modulation for safer orthodontic outcomes.[29]

Comparison of Intrusion with and Without Attachments

Attachments significantly enhanced stress distribution and intrusion precision in both protocols. Without attachments, stress concentration was higher, leading to increased root apex displacement and tipping. The reduction in von Mises stress with attachments was 25% in the conventional method and 30% in the Frog staging protocol, indicating better force control and predictability. Additionally, displacement decreased by 33% with attachments in conventional intrusion and 42% in Frog staging. These findings are consistent with studies on aligner therapy, which emphasize the role of attachments in controlling stress vectors and minimizing undesired tooth movement.[30-32]

Group-wise Comparison

- Conventional intrusion without attachments: Maximum displacement of 0.18 mm, von Mises stress of 20 MPa, and increased root apex stress.
- Conventional intrusion with attachments: Displacement reduced to 0.177 mm, stress lowered to 15 MPa, with improved control over unwanted tipping.
- Frog staging intrusion without attachments: Displacement at 0.092 mm, stress at 12 MPa, showing better control than conventional methods.
- Frog staging intrusion with attachments: Demonstrated the most balanced biomechanics, with displacement limited to 0.090 mm and von Mises stress at 10 MPa.

While previous studies have explored aligner-based intrusion, few FEM studies have specifically compared stress and displacement patterns in different intrusion protocols. Clinical studies have reported high variability in aligner-driven incisor intrusion outcomes, often attributing tipping effects to inadequate force control.[33] Our findings provide biomechanical evidence supporting sequential force application in Frog staging to reduce stress intensity and improve intrusion predictability. This finding is also supported by other studies.[34,35]

Strengths, limitations, and future directions

This study is one of the first to use FEM analysis to compare conventional and Frog staging intrusion protocols with and without attachments. The high-resolution model and detailed stress analysis provide novel insights into aligner biomechanics. The key strength lies in its ability to quantify stress and displacement trends, offering clinical relevance for optimizing aligner-based deep bite correction. However, limitations include the absence of clinical validation and inter-individual variability in biological responses. Future studies should incorporate patient-specific data and clinical trials to corroborate these findings. Additionally, exploring the impact of different attachment shapes and materials on intrusion mechanics can further enhance treatment predictability.[36-38]

With the advent of direct-printed aligners that can be used without attachments, future studies should focus on the wear and degradation patterns of various aligner materials, as well as evaluate the role of attachments and their mechanical integration, along with long term stability of the achieved results to enhance the clinical relevance of in vitro simulations.[39-43]

Conclusion

- The results highlight the biomechanical superiority of the Frog staging protocol with attachments in achieving controlled incisor intrusion.

- Compared to conventional intrusion, this method significantly reduced stress concentration, minimized root apex displacement, and maintained true intrusion along the root axis. These findings contribute to the existing literature by providing FEM-based evidence supporting sequential intrusion mechanics, offering a more predictable and safer approach for clear aligner therapy.
- Further research is warranted to validate these results in clinical settings and refine treatment protocols based on individual patient biomechanics.

Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent forms. In the form the patient(s) has/have given his/her/their consent for his/her/their images and other clinical information to be reported in the journal. The patients understand that their names and initials will not be published and due efforts will be made to conceal their identity, but anonymity cannot be guaranteed.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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