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Research Article

Impact of screw arm angle, material property, and applied force on the behavior of maxillary expander

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ABSTRACT

A unilateral or bilateral posterior crossbite is a common and severe malocclusion characterized by maxillary transversal deficiency. Various expansion appliances are employed to correct this condition. The objective of this study was to evaluate the forces transmitted to the teeth and the deformation of the expander appliance resulting from modifications to the screw arms of a slow maxillary expander with different angles, using finite element analysis. All models were created in SolidWorks and analyzed using ANSYS Workbench. The analysis revealed that the models with different angular configurations of the expander screw arms (0°, 15°, and 30°) exhibited very similar reaction forces on the teeth. However, significant differences in deformation values were observed among the models. The most effective parameter is the force applied to the expander with a rate of 46%, followed by the arm angle with a rate of 44%, while the effect of material type is 10%. The most significant conclusion that can be drawn from these findings is that the arm angle is as important as the force applied to the expander. In situations where the force that can be applied is limited by various factors, it can be demonstrated that altering the arm angle can lead to the achievement of the desired outcome.

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1. Introduction

Transversal maxillary deficiency (TMD) is a prevalent malocclusion that necessitates early intervention in orthodontics. The transverse dimensional discrepancy in maxillo-mandibular relationships often leads to the development of posterior crossbite, which can be either unilateral or bilateral. Posterior crossbite is particularly common during the mixed dentition (Da Silva Filho et al. 2007; Leonardi et al. 2018). Unilateral posterior crossbite is typically associated with lateral displacement of the mandible, resulting from maxillary transverse deficiency in maximal intercuspation. This condition causes the mandibular midline to shift toward the side of the crossbite (Alsawaf et al. 2022; Kutin and Hawes 1969). Such a change has been shown to lead to the development of craniofacial asymmetry in adulthood. Therefore, early diagnosis and management of this condition is essential to prevent long-term functional and aesthetic complications (Tsanidis et al. 2016).

Traditional rapid maxillary expanders (RMEs) are widely recognized as effective for correcting TMD (Silveira et al. 2021). These devices deliver heavy and intermittent forces to the dento-skeletal structures, promoting rapid expansion (Isaacson and Ingram 1964; Haas 1970). In contrast, slow maxillary expanders (SMEs) aim to achieve more gradual expansion by focusing on maximizing dental effects while applying lower, continuous force levels (Andrew 1985). Furthermore, nickel-titanium (Ni-Ti) expanders have been introduced, which

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provide continuous, low-level force application, enhancing comfort and treatment efficiency (Arndt 2004; Wichelhaus et al. 2004). Among these, the Ni-Ti Memoria Leaf Spring Self-Activated Expander has been developed as an innovative expansion device, further optimizing the expansion process (Gianolio et al. 2015). It has been reported that the Ni-Ti MEMORIA® Leaf Spring Expander is utilized in growing patients for the correction of transverse maxillary insufficiency. It provides adequate expansion without significantly tipping the teeth and is regarded as an effective device for slow expansion when used in accordance with the recommended protocol (Manzella et al. 2018). Furthermore, research has shown that both the Rapid Palatal Expander and the Leaf Expander induce similar changes in palatal surface area in individuals with maxillary transverse deficiency during the mixed dentition period (Silvestrini-Biavati et al. 2024; Ugolini et al. 2025). It has been confirmed that these two expanders produce comparable skeletal and dental effects in subjects (Lanteri et al. 2021; Inchingolo et al. 2023).

Similar to the SME protocol, the leaf expander is an innovative device characterized by a double nickel-titanium leaf spring, in addition to a midline jack screw. The screw is pre-activated in the laboratory, and the orthodontist can activate the leaf springs by compressing them, generating a constant force of either 450 g or 900 g. The primary benefits of using this device are its ease of activation and the fact that it does not require patient cooperation during the expansion process (Salgueiro et al. 2015; Inchingolo et al. 2023). Previous studies have evaluated the effects of 6 mm and 10 mm expander options in patients with mixed and permanent dentition (Lanteri et al. 2016; Manzella et al. 2018).

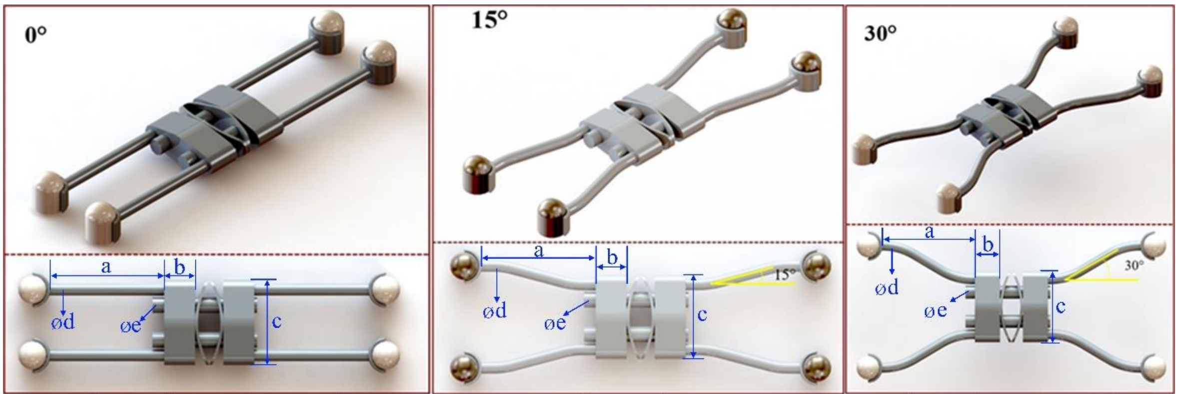
Finite element analysis (FEA) is a well-established method for structural simulation and mechanical analysis, widely applied in research on maxillary expansion (Lee et al. 2017). By substituting complex structures with a finite number of elements having simple geometric shapes, FEA plays a crucial role in the field of medical biomechanics (Pan et al. 2024; Shetty et al. 2009). To date, the evaluation of Ni-Ti Memoria Leaf Spring Activated Expander arm modifications has been limited to a single in vitro study (Lowe et al. 2020).

However, there is still a lack of comprehensive research examining the various material properties and mechanical modifications of the slow maxillary expander, particularly those involving the leaf-shaped elements. The objective of this study was to evaluate the deformation of the slow expander and the forces transmitted to the teeth as a result of applying different configurations to the slow maxillary expander screw arms, using FEA.

2. Materials and Method

2.1. Geometric details and material properties

The present study encompasses three distinct maxillary expander geometries. Given that all other components remain identical, the expander forms an angle of 0º, 15º and 30º relative to the teeth in each configuration, respectively. The designed expander geometries are illustrated in Fig. 1.



a (mm)	b (mm)	c (mm)	d (mm)	e (mm)	a (mm)	b (mm)	c(mm)	d(mm)	e (mm)	a (mm)	b (mm)	c(mm)	d (mm)	e (mm)
15	4	11	1.5	2	15	4	11	1.5	2	15	4	11	1.5	2

Fig. 1. The geometries and dimensions of maxillary expander with 0°, 15° and 30° arm angle.

The materials that were considered for use in the maxillary expander included the Ti6Al4V alloy, 316-L stainless steel and CoCr alloy. The mechanical properties of these materials are outlined in Table 1.

Table 1. Material properties used in finite element analysis (Karslı et al. 2024; Karaman et al. 2022).

Material	Young's modulus (GPa)	Poisson's ratio
Ti6Al4V	113.8	0.34
316-L	193	0.25
CoCr	213	0.28
Tooth	19.6	0.3

2.2. Finite element model

Numerical studies were conducted utilizing ANSYS Workbench, a commercial finite element software. Given that the stresses are not expected to exceed the yield stress, and the loadings are minimal, the analyses were performed employing a linear-elastic material model. Fig. 2 illustrates the mesh structure for each configuration. For all components of the expander, an element size of 0.15 mm was selected, taking into account the mesh dependency. A mesh convergence analysis was conducted on three distinct element sizes (0.10, 0.15 and 0.20 mm). Following the implementation of the 0.15 mm element size, no substantial alterations were observed in the results or mesh metrics. Consequently, 0.15 mm was selected as the optimal element size. The mesh metrics are presented in Table 2.

The boundary conditions are illustrated in Fig. 3. Due to the computational expense, the two leaf springs located at the center of the expander (Fig. 1) were excluded from the finite element model, with the forces generated by the springs being incorporated directly into the finite element model. The expander sliding on the pins exerts three different forces of 2.943 N, 5.886 N and 8.829 N in both directions in the x-axis, respectively, on the teeth fixed from the bottom surface. Three different expander arm angles, three different material types and three different loading magnitudes were taken into consideration in this study and a total of 27 FEA were performed to obtain the equivalent stresses and deformations in x-direction. The analysis parameters are given in Table 3.

Table 2. Mesh metric values for all finite element analysis configurations.

Configuration	Number of elements	Number of nodes	Element quality
0°	250,279	1,067,591	0.870±0.11
15°	169,140	733,522	0.879±0.12
30°	194,590	832,970	0.860±0.12

Table 3. Finite element analysis parameters for maxillary expander.

Parameters		
Arm Angle	Material	Load (N)
0°	Ti6Al4V	2.943
15°	316-L	5.886
30°	CoCr	8.829

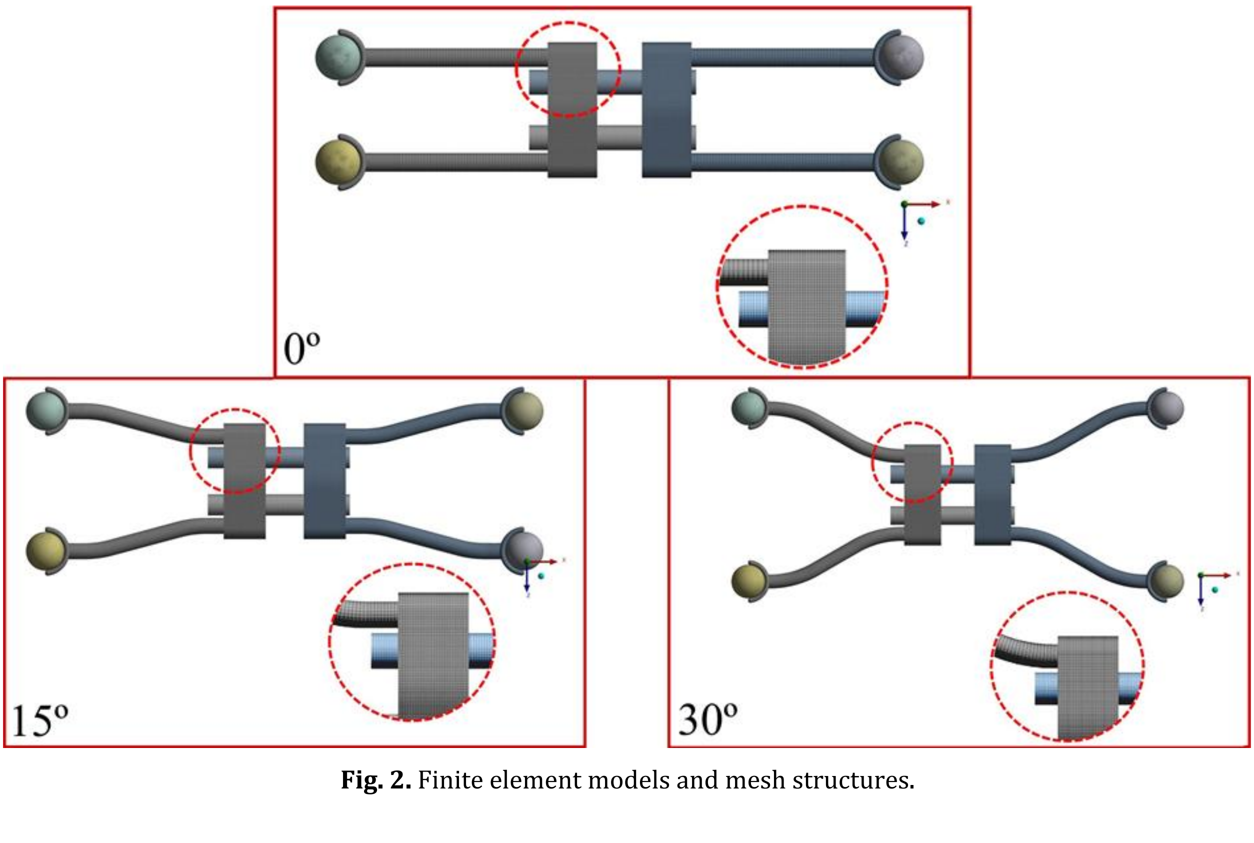


Fig. 2. Finite element models and mesh structures.

2.3. ANOVA analysis

In order to ascertain the effect of arm angle, material and load on equivalent stress and deformation in the x-direction, an analysis of variance (ANOVA) test was performed using Minitab software. A parameter was deemed to be statistically significant if $p < 0.05$. The effect of each parameter was explained with graphs showing the S/N ratios obtained. In this statement, the signal value (S) is the value to be measured, and the noise value (N) is the effectiveness of the undesired factors within the measured value. The graphs of the calculated S/N ratios represent the degree of influence of any variable parameter used in the analysis. In addition to the S/N ratio, ANOVA analysis was used to determine the significance levels of variable parameters affecting the mechanical properties of the structures. This analysis was performed with Minitab software (Ghahramanzadeh Asl et al. 2023).

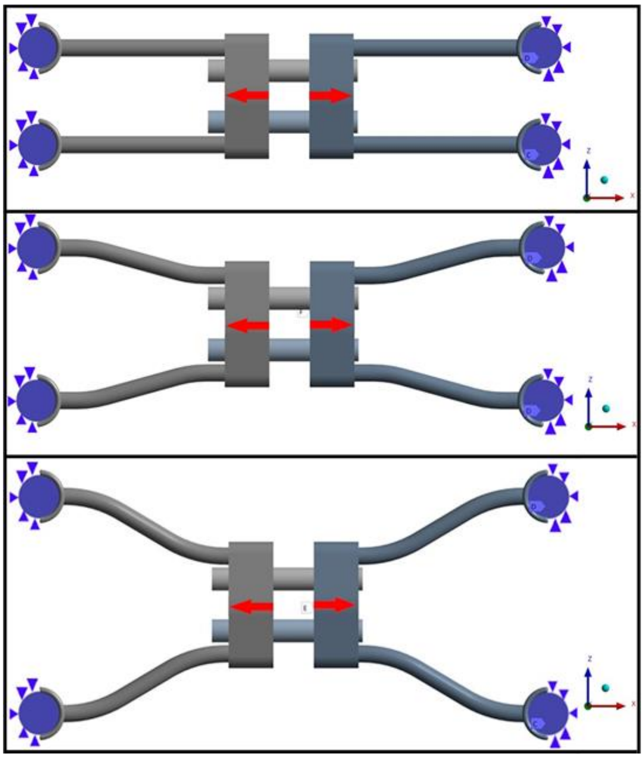


Fig. 3. Boundary conditions of models.

3. Result and Discussion

3.1. Finite element analysis results

As illustrated in Figs. 4–6, the FEA of the expanders with arm angles of 0°, 15° and 30° reveals the equivalent stress and deformation results in the x-direction.

The maximum equivalent stress and maximum deformation in the x-direction results obtained from all configurations are presented comparatively in Figs. 7 and 8, respectively.

When the equivalent stresses were analyzed, the situation was reversed. In each configuration, the stress reached a maximum at the screw arms, while it was significantly lower at the center and at the endpoints in contact with the threads. The only difference between the configurations is related to the stress distribution in the arms. In the expander with an arm angle of 0°, a more homogeneous stress distribution was observed due to the linear arm geometry. In contrast, in the expanders with arm angles of 15° and 30°, stress concentration occurred in the curved regions due to the geometry of the arms. However, since the maximum equivalent stress obtained (19.233 MPa) is nowhere near the yield stress for all three expander materials, there is no cause for concern.

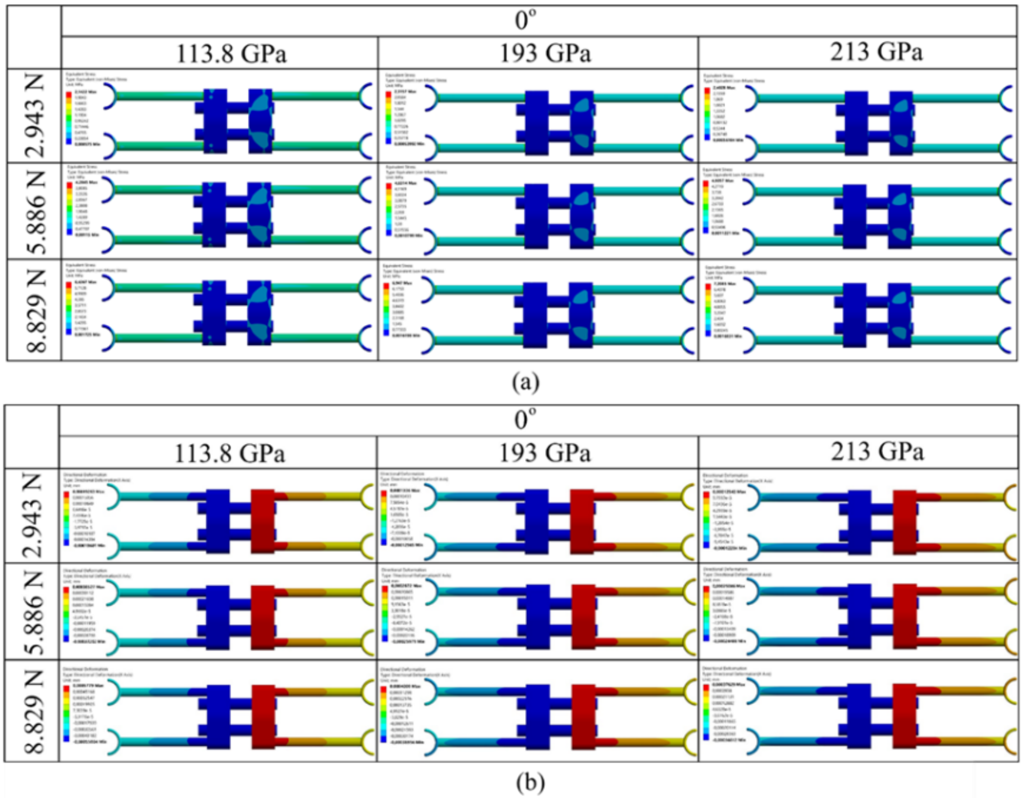


Fig. 4. Finite element analysis results for 0-degree arm angle:
(a) Equivalent stress distribution; (b) Directional deformation along x-direction.

It can be posited that the maximum and minimum deformation in the x-direction are nearly equivalent for all three configurations, with deformation concentrated at the center of the expander. This observation is consistent with the anticipated outcomes, given the location where the force was applied to the expander in both directions (Fig. 3). However, for expanders with arm angles of 15° and 30°, an increase in deformation was observed at the ends of the areas in contact with the teeth.

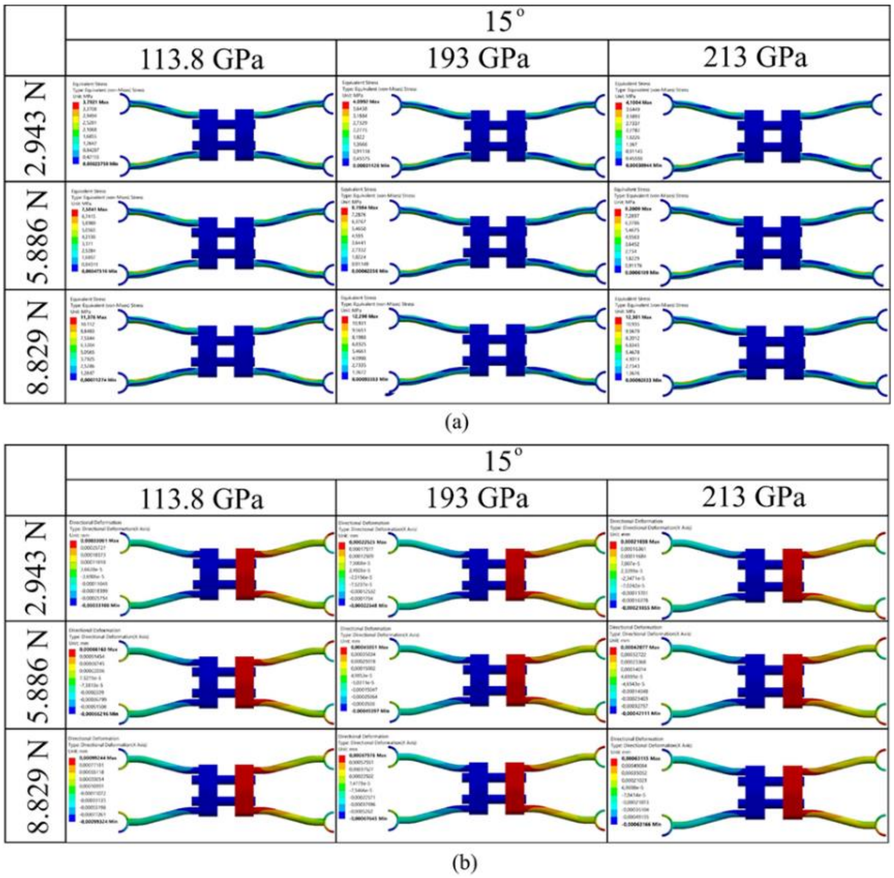


Fig. 5. Finite element analysis results for 15-degree arm angle:
(a) Equivalent stress distribution; (b) Directional deformation along *x*-direction.

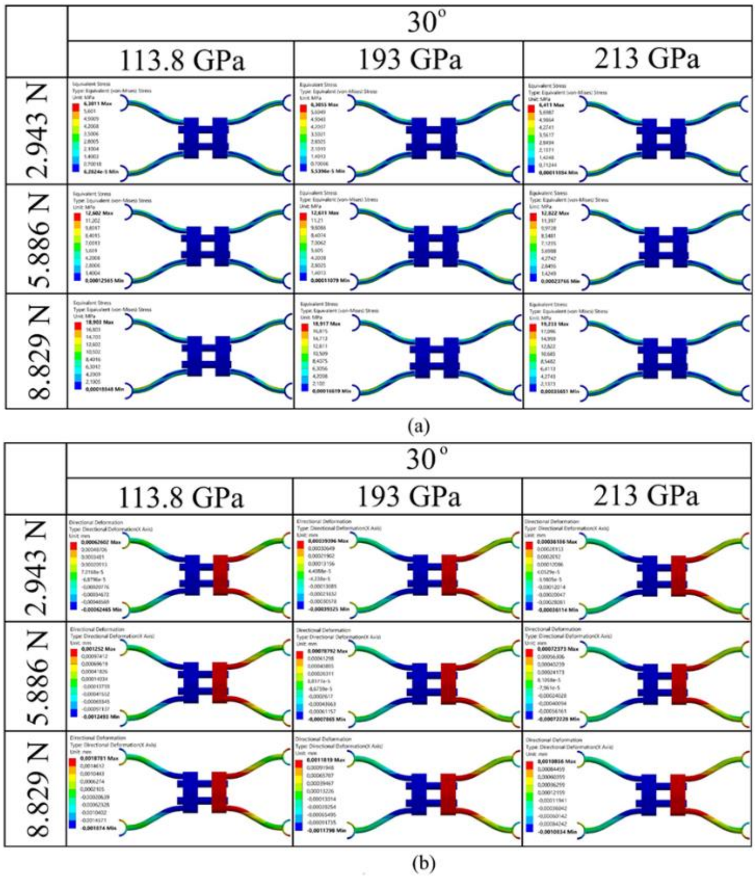


Fig. 6. Finite element analysis results for 30-degree arm angle:
(a) Equivalent stress distribution; (b) Directional deformation along *x*-direction.

When the configurations for each angle value were evaluated individually, it was observed that the maximum equivalent stress increased as the rigidity of the material used for the expander increased. Conversely, as predicted, expander deformation decreased with increasing elastic modulus. In accordance with the linear-elastic analysis, it was observed that as the applied force increased, the maximum equivalent stress also increased at the same rate. This increase was reflected in the maximum deformation as well. A noteworthy observation is the impact of the expander arm angle on both maximum stress and deformation.

It is evident that as the arm angle increases, both the maximum stress and deformation also increase, indicating a dependence on arm geometry. It is also important to note that as the expander screw arm angle increases, the curvature increases, leading to higher stress concentrations.

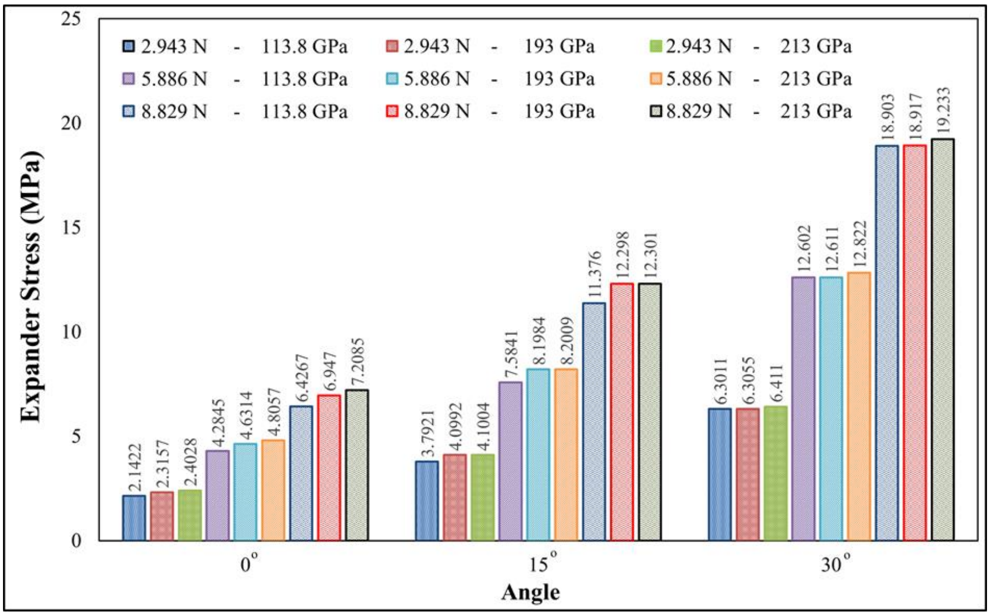


Fig. 7. Comparative maximum equivalent stress results for all configurations.

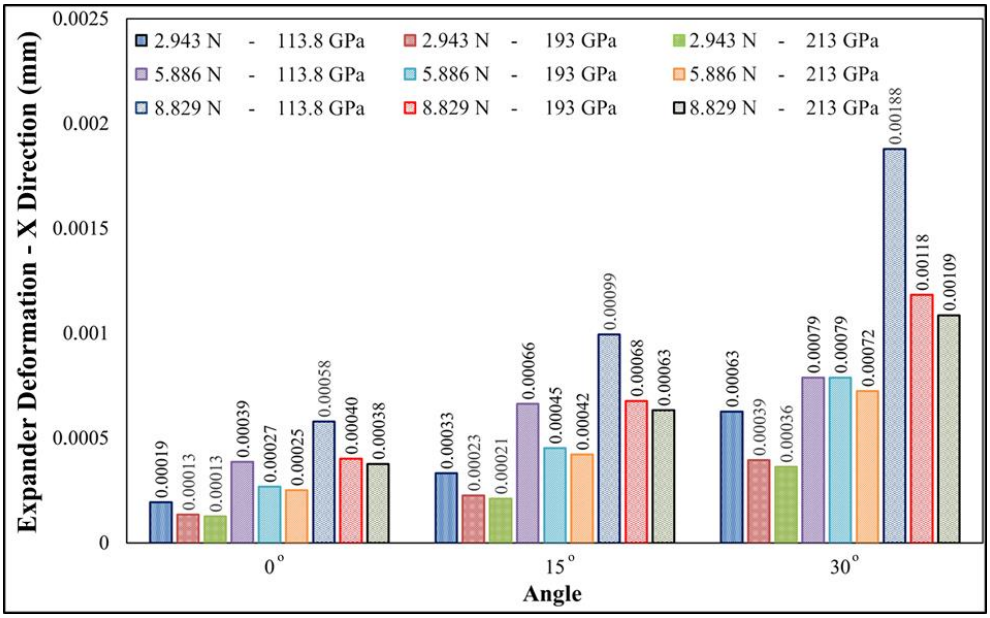


Fig. 8. Comparative maximum deformation results of expander along *x*-direction for all configurations.

The effect of the expander on the displacement of the tooth in the *x*-direction is comparatively given in Fig. 9 for all configurations. When Fig. 9 was analyzed, it was observed that the primary factor influencing tooth displacement was the force applied to the expander, while material type and arm angle had no significant effect. However, it would be erroneous to interpret tooth displacement in this manner. In actual practice, the expander remains in the upper jaw for extended periods, exerting continuous force. This temporal aspect is not feasible to incorporate within finite element analysis. Consequently, the tooth deformation depicted in Fig. 9

represents instantaneous deformations corresponding to the force application, without accounting for the duration of force application.

Additionally, the fixed position of the teeth from below, as illustrated in Fig. 3, contributes to this phenomenon. Consequently, the most efficacious method of interpreting the deformation occurring in the tooth/jaw by finite element analysis is to interpret the results through the expander. Furthermore, measuring the reaction forces between the expander and the tooth can also provide some insight, and the relevant results are given in Fig. 10.

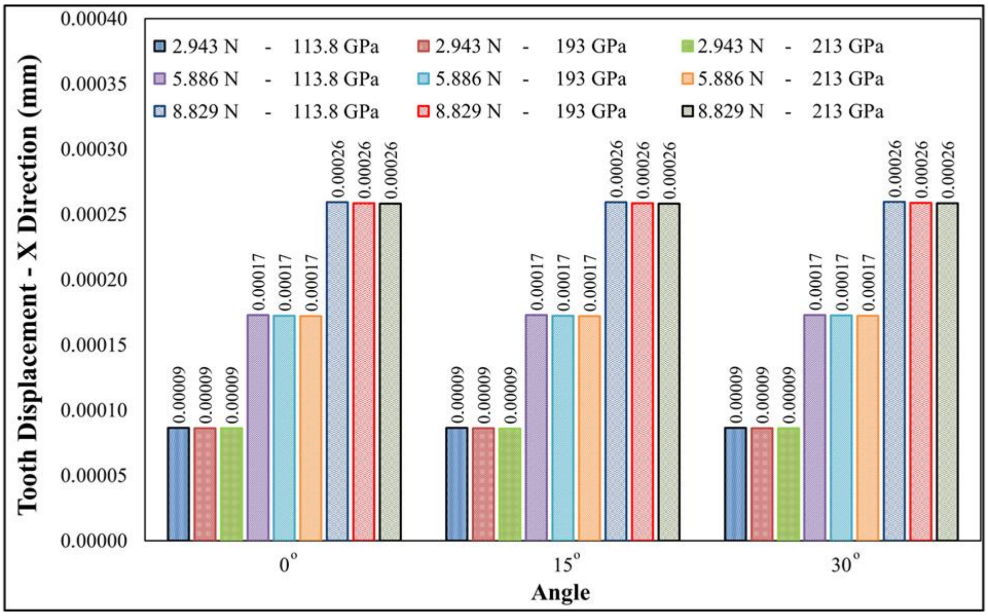


Fig. 9. Comparative maximum deformation results of tooth along x-direction for all configurations.

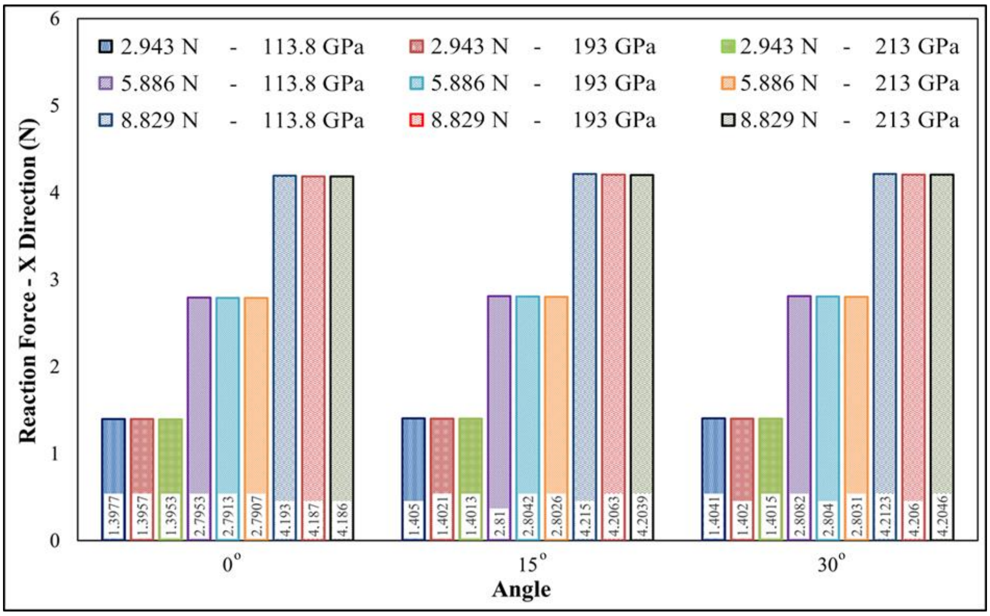


Fig. 10. Comparative maximum reaction force results along x-direction for all configurations.

As demonstrated in Fig. 10, a comparative analysis of the reaction forces in the x-direction is provided for all configurations. In accordance with the predictions, the reaction force increases in proportion to the applied force to the expander. However, the effect of material properties and arm angle is not significant, as discussed in the preceding section. However, a detailed analysis of Fig. 10 reveals that as the elastic modulus of the preferred material increases for the expander with each arm angle, the reaction force in the x-direction decreases, albeit in small amounts. This is an important sign that tooth deformation increases as the elastic modulus increases.

Similarly, when the arm angle is 15°, there is an increase in the reaction force compared to 0°. However, no significant disparities were identified between configurations with an arm angle of 30° and those with an arm angle of 15°.

3.2. ANOVA results

The results obtained from the analysis of variance (ANOVA) test using the maximum expander deformations in the *x*-direction obtained from the FEA are presented in Fig. 11. According to this, the most effective parameter is the force applied to the expander with a rate of 46%, followed by the arm angle with a rate of 44%, while the effect of material type is 10%. The most significant conclusion that can be drawn from these findings is that the arm angle is as important as the force applied to the expander. In situations where the force that can be applied is limited by various factors have been examined. As a result of the examination, it can be demonstrated that altering the arm angle can lead to the achievement of the desired outcome. This suggests that by modifying the arm angle, it is possible to achieve superior results by applying a lesser amount of force.

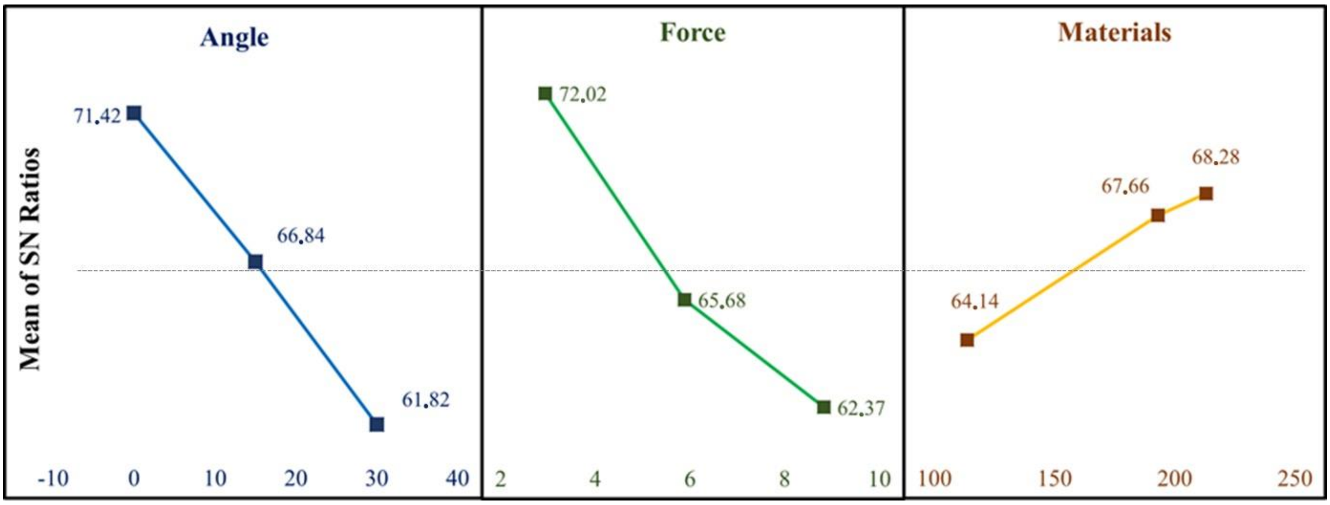


Fig. 11. ANOVA test results based on maximum deformation of expander along *x*-direction.

4. Conclusions

This study aims to evaluate the deformation of the slow expander, and the forces transmitted to the teeth. Three different expander arm angles (0°, 15° and 30°), three different material types (Ti6Al4V, 316-L and CoCr alloy) and three different loading magnitudes (2.943 N, 5.886 N and 8.829 N) were considered. In addition, total of 27 finite element analyses were performed. Based on the results obtained, the following conclusions were reached:

- An increase in the arm angle of the expander led to greater deformation within the tooth contact areas.
- A more homogeneous stress distribution was achieved in the expander with a screw arm angle of 0 degrees; however, stress concentrations were observed in the curved regions as the screw arm angle increased.
- In all screw angle configurations, an increase in the Young's modulus of the expander material resulted in greater deformation of the expander.
- The results of the ANOVA analysis indicated that the screw arm angle is as significant as the force applied by the expander. In situations where sufficient force cannot be applied due to various constraints, better results may be achieved by adjusting the screw angle
- The applied force was found to have a more significant impact on expander deformation compared to the other variables.
- In cases where a high force is applied to the leaf expander, it is crucial to consider the potential deformations that may occur.

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Conflict of Interest
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Author Contributions
All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability
The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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