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BASIC RESEARCH:

Three-Dimensional Finite-Element Study into the Biomechanical Comparison of Force Distribution in Self-Ligating and Conventional Brackets

Estudio tridimensional por elementos finitos sobre la comparación biomecánica de la distribución de fuerzas en brackets autoligables y convencionales

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ABSTRACT: The distribution of force in orthodontic treatments greatly affects outcome variables, including tooth movement efficiency and periodontal health. The aim of this study was to analyze the force distribution in self-ligating and conventional brackets during anterior tooth retraction through finite element analysis (FEA). Micro-CT scans and solid modeling software created a 3D model of the maxillary central incisor and supporting components. Clinical orthodontic protocols for anterior retraction were used to define boundary conditions and force magnitudes for ANSYS 2020R2 finite element simulations. Self-ligating brackets (Damon Q1, Q2) were used with edgewise, Roth, and MBT brackets. Stress distribution in the tooth, PDL, and surrounding alveolar bone was investigated under simulated orthodontic forces. The FEA revealed significant differences in stress distribution among the bracket types. The self-ligating Damon Q1 and Q2 brackets exhibited a more uniform stress distribution compared to conventional brackets, which showed concentrated stress in the crown and root areas. Maximum stress values in the Damon Q2 bracket were found to be lower (0.99984 MPa) and more evenly distributed across the tooth and PDL, suggesting more efficient force application. In contrast, the edgewise bracket demonstrated higher localized stresses, particularly at the crown and apical regions. Self-ligating brackets produce a more predictable and biologically acceptable force distribution than conventional brackets. These findings may lower root resorption risk and enhance treatment predictability. Interpreting these findings should take into account limitations like the simplified tooth model and lack of *in vivo* confirmation.

KEYWORDS: Finite element analysis; Medicine; Torque; Self-ligating bracket; Stress distribution.

RESUMEN: La distribución de fuerzas en los tratamientos ortodónticos influye significativamente en variables de resultado como la eficiencia del movimiento dental y la salud periodontal. El objetivo de este estudio fue analizar la distribución de fuerzas en brackets de autoligado y convencionales durante la retracción de dientes anteriores, mediante análisis por elementos finitos (FEA, por sus siglas en inglés). A partir de escaneos por microtomografía computarizada (micro-CT) y el uso de un software de modelado sólido, se generó un modelo tridimensional del incisivo central maxilar y sus estructuras de soporte. Se aplicaron protocolos clínicos ortodónticos para la retracción anterior a fin de definir las condiciones limitantes y las magnitudes de fuerza para las simulaciones por elementos finitos en ANSYS 2020R2. Se emplearon brackets de autoligado (Damon Q1 y Q2) y brackets convencionales tipo edgewise, Roth y MBT. Se evaluó la distribución de estrés en el diente, el ligamento periodontal (PDL) y el hueso alveolar circundante bajo fuerzas ortodónticas simuladas. El análisis por elementos finitos reveló diferencias significativas en la distribución de fuerzas entre los distintos tipos de brackets. Los brackets de autoligado Damon Q1 y Q2 mostraron una distribución de fuerzas más uniforme en comparación con los brackets convencionales, los cuales presentaron concentraciones de estrés en las áreas coronarias y radiculares. Los valores máximos de estrés en el bracket Damon Q2 fueron menores (0,99984 MPa) y más homogéneamente distribuidos a lo largo del diente y el ligamento periodontal, lo que sugiere una aplicación de fuerzas más eficiente. En contraste, el bracket edgewise evidenció mayores concentraciones localizadas de fuerzas, especialmente en las regiones coronal y apical. Los brackets de autoligado generan una distribución de fuerzas más predecible y biológicamente aceptable que los brackets convencionales. Estos hallazgos podrían reducir el riesgo de reabsorción radicular y mejorar la predictibilidad del tratamiento. La interpretación de estos resultados debe considerar limitaciones como la simplificación del modelo dental y la ausencia de confirmación *in vivo*.

PALABRAS CLAVE: Análisis por elementos finitos; Ortodoncia; Torque; Brackets de autoligado; Distribución de fuerzas.

INTRODUCTION

Malocclusion is regarded by the WHO as one of the most significant oral health issues, second only to caries and periodontal disease. Its prevalence is highly varied, with estimates ranging from 39% to 93% among children and adolescents (1). Orthodontic treatment has been thoroughly explored due to significant public awareness regarding malocclusion and the necessity for aesthetic enhancement. It seeks to provide optimal aesthetics, proper tooth alignment, harmonic occlusion, and a favorable interaction between teeth and their supporting structures (2). Accelerating orthodontic tooth movement reduces treatment time, which lowers the risk of enamel decalcification, caries, periodontal tissue destruction (gingivitis and periodontitis), and root resorption (3). As a result, any appliance treatment capable of accelerating the progression of teeth alignment represents a potential clinical advancement. On the other hand, excessive forces and rapid tooth movement may have detrimental effects (4). It is essential to assess every new appliance system for its capacity to align teeth efficiently and reliably, while minimizing adverse effects on the oral tissues. The availability of self-ligating orthodontic equipment for clinicians has significantly risen in recent years. The Damon system has garnered interest for its implementation of passive self-ligating brackets. This technique is lauded for its efficacy in addressing various malocclusions, often resulting in a diminished necessity for extractions, surgical procedures, or palatal expansion, while reportedly alleviating patient discomfort and expediting treatment duration. The Damon system emphasizes improvements in mechanical performance and clinical management, using a low-friction bracket design that facilitates the administration of light, continuous forces during tooth movement (5,6).

Direct measurement of force and associated biological responses *in vivo* is challenging, necessitating the development of indirect investigative methods. Finite element analysis (FEA) has emerged as a significant computational technique for simulating mechanical action in biological tissues and synthetic materials, eliminating the necessity for invasive procedures (7,8). FEA is commonly used in orthodontics to study force distribution, dentofacial displacement patterns, appliance comparisons, and resistance centers. Advanced digital imaging and modeling software can provide exact clinical settings for biomechanical simulations. These advances let researchers evaluate orthodontic equipment more accurately, efficiently, and safely, anticipate treatment outcomes, and optimize clinical protocols (8,9). This study applied FEA to assess and contrast the biomechanical performance of various orthodontic bracket systems-namely edgewise brackets and Damon Q1/Q2 self-ligating brackets-concerning stress distribution in the tooth roots and adjacent periodontal tissues. This study aims to test the hypothesis that self-ligating brackets produce a more favorable force distribution and lower stress on tooth roots and periodontal tissues during anterior tooth retraction compared to conventional edgewise brackets, as evaluated using 3D FEA.

MATERIAL AND METHODS

This research received approval from the ethical committee of XXX, under the designation No.086/KE/FKG-UGM/EC/2022. An adult male subject with Class II Division 1 angle malocclusion underwent dental and maxillary bone remodeling via cone-beam computed tomography (CBCT) scanning. The subject exhibited a proclined upper incisor to the NA line (U1-NA) of 40.99°, indicating the necessity for premolar extraction, with no anomalies in bone structure. A CBCT imaging device (Genoray, Korea, 60 kVp, 60 mAs) was utilized to acquire a dental model of the patient, subsequently reconstructed in FEA. The scan data was imported in DICOM format and used for reconstruction purposes. This experiment utilized only half of the dentition (half-arch) based on the premise of symmetry in human upper and lower dentitions. The STL files were generated by selecting the maxillary right central incisor and its corresponding alveolar bone. The STL files were subsequently imported for reverse engineering reconstruction, during which the models were optimized through flattening, denoising, meshing, and surface fitting. The dental components, periodontal ligament, palatal bone, and maxillary alveolar bone were combined to create a three-dimensional model (Table 1).

Table 1. Average material property values.

Material	Young's Modulus (MPa)	Poisson's Ratio
Bone	$2x10^3$	0.3
Periodontal Ligament	Bilinear: E_1= 0.05, E_2= 0.20, ε_{12}=7.0%	0.3
Tooth	$2x10^4$	0.3
Adhesive (Resin)	8823	0.25
Bracket and Archwire (Stainless Steel)	$2x10^5$	0.3

This work utilized three-dimensional (3D) FEA to examine the biomechanical behavior of a proclined maxillary central incisor (U1), which necessitates anterior retraction for optimal tooth alignment. The anatomical model of the maxillary incisor and its supporting components was created utilizing SolidWorks (Dassault Systèmes, France), a sophisticated 3D computer-aided design (CAD) software. The modeling approach entailed rebuilding the crown, root, periodontal ligament (PDL), and adjacent alveolar bone with accurate anatomical measurements derived from normal dental morphology. The tooth's initial condition was deliberately designed in a proclined position to simulate a typical clinical situation in orthodontics where retraction mechanics are utilized for incisor uprighting.

To improve the precision of the bracket and wire arrangement utilized in the simulation, micro-computed tomography scanning was conducted employing a Dino-Lite Digital Microscope with micrometer-level resolution. This facilitated high-fidelity 3D imaging of the bracket base, slot dimensions, and lock-hook components, specifically for the edgewise bracket model, roth bracket model, mbt bracket model, Self-ligating damon Q1 bracket model, and Self-ligating damon Q2 bracket model (Figure 1). The scanned photos were transformed into digital files and incorporated into the 3D model to accurately reproduce the clinical environment. Upon finalization of the complete geometry of the tooth-bracket-archwire assembly, it was loaded into ANSYS 2020R2 (ANSYS Inc., USA), a prevalent commercial software for finite element modeling and simulation. Upon completion of the geometric modeling in systems, the subsequent phase was the creation of the finite-element model, which included generating a mesh from Parasolid files within the SolidWorks Simulation software. The meshing method produced 96,154 nodes and 198,674 elements for the creation of 3D models. The convergence test was performed by examining models with progressively higher mesh density. The displacement and stress values exhibited a change of less than 2% between the two finest meshes, signifying numerical convergence and validating the accuracy and reliability of the FEA results.

Boundary conditions and loading parameters were meticulously established to simulate clinical retraction mechanics. A force vector was exerted on the archwire along the Z-axis, simulating anterior retraction (Figure 2). The force magnitude was determined according to established orthodontic protocols for incisor movement, with a sensitivity study conducted to confirm the chosen force range. Sensitivity investigation is the process of analyzing how the output of FEA model varies in response to alterations in the input parameters, such as material properties, boundary conditions, geometry, mesh size, and loads. The basal surface of the alveolar bone was characterized as a rigid support, limiting all degrees of freedom to replicate the stability of the craniofacial skeleton *in vivo*.

Material properties for each component were designated according to values documented in the literature. The maxillary incisor and alveolar bone were regarded as linearly elastic and isotropic, whereas the periodontal ligament was characterized as a non-linear, viscoelastic material to more precisely represent its biological response to orthodontic forces. Stainless steel 0.021″ x 0.025″ were applied to the archwire depending on the bracket system being analyzed. The simulation was conducted to assess various mechanical responses, including average and maximum von Mises stress distribution in the tooth and PDL.

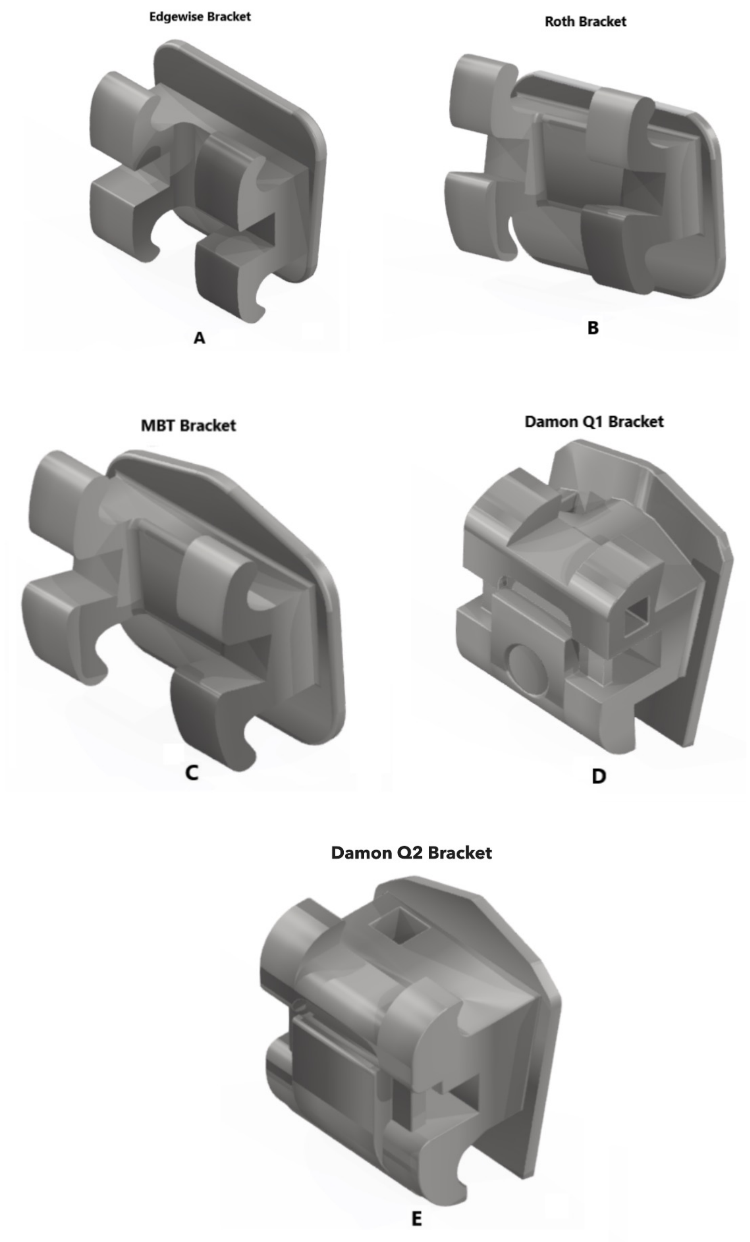

Figure 1. (A) Edgewise Bracket Model, (B) Roth Bracket Model, (C) MBT Bracket Model, (D) Self-ligating Damon Q1 Bracket Model, (E) Self-ligating Damon Q2 Bracket Model.

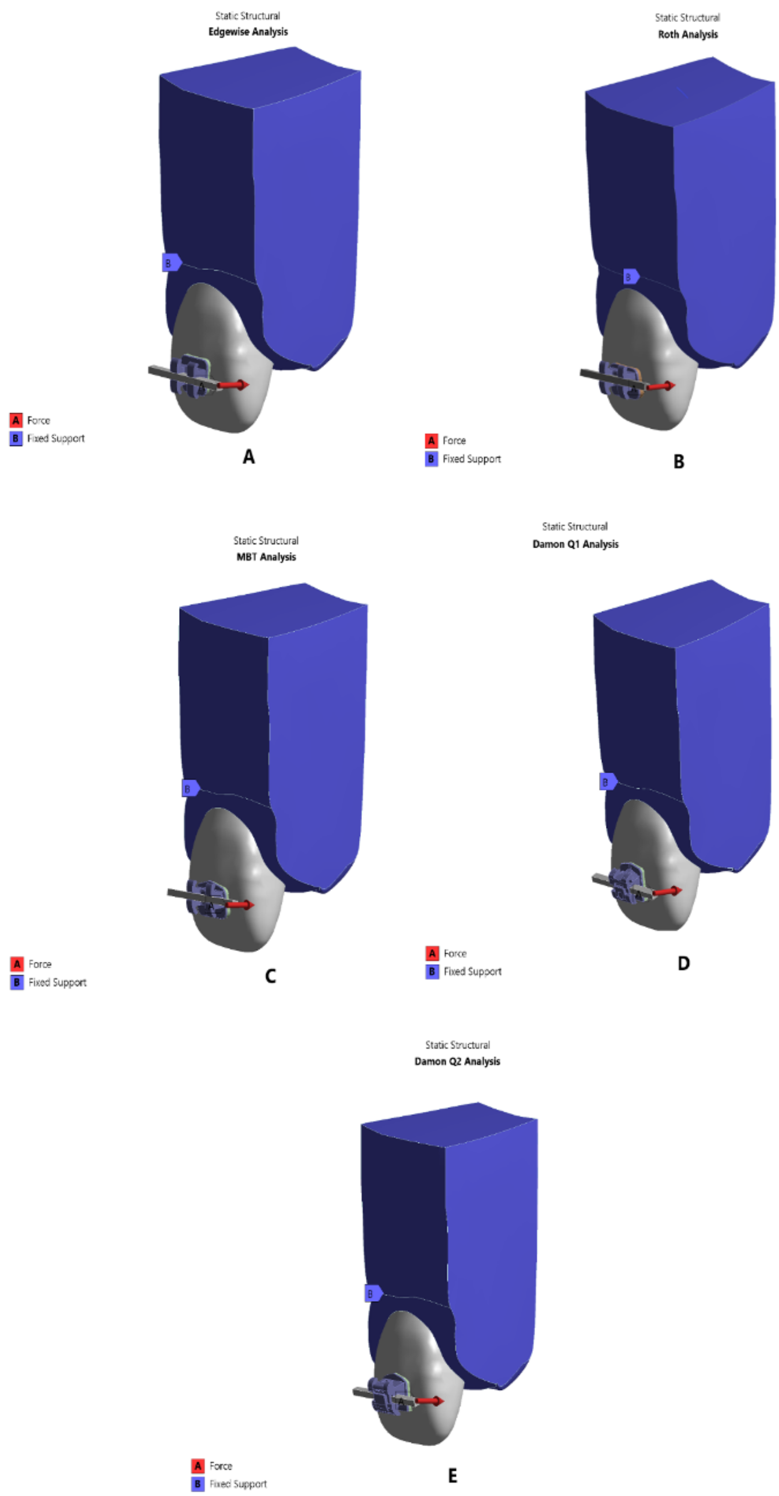

Figure 2. Simulation Setup (A) Edgewise Bracket, (B) Roth Bracket, (C) MBT Bracket, (D) Damon Q1 Bracket, (E) Damon Q2 Bracket.

RESULTS

The FEA performed in this study examines the distribution of mechanical stress across various orthodontic bracket systems. The results are mainly shown as descriptive color maps, with a few maximum stress values for important reference points, as shown in Table 2. The analysis uses von Mises stress as the primary parameter to evaluate the biomechanical response of the brackets under typical orthodontic loading conditions. A color-mapped stress distribution was utilized to visualize the varying stress levels, with red indicating the highest stress concentrations, green representing intermediate levels, and blue reflecting the lowest stresses. These visual representations are intended to highlight areas of concern but are supplemented by quantitative comparisons to provide a more comprehensive understanding of the stress distribution.

The equivalent (von Mises) stress in the longitudinal section (Figure 3) and labial palatal (Figure 4) reveals a notable disparity in the distribution pattern between each bracket systems. The Edgewise bracket simulation, for example, shows an excessive amount of stress in the labial and apical areas, with a peak von Mises stress of 0.91242 MPa. The Damon Q1 and Q2 brackets, on the other hand, demonstrate much lower stress levels, with von Mises stresses of 0.98345 MPa and 0.99984 MPa, respectively. This means that the stress is more evenly spread across the tooth and periodontal ligament.

The pressure distribution on the PDL reinforces up these results even more. The FEA research concentrating on the pressure within the periodontal ligament region yielded linked outcomes (Figure 5). The Edgewise bracket has a very uneven stress distribution. The highest stress, 0.50487 MPa, is in a large red area, while the lowest stress is in large orange and blue areas. On the other hand, both the Roth and MBT brackets show fewer high-pressure zones, especially in the root area. This suggests that the force is being applied more evenly. The Damon Q1 and Q2 brackets, especially Damon Q2, have the best stress distribution. There are very few high-pressure zones, and the blue area shows that the stress is low. The blue color looks most dominant from the coronal to the root area. There is no red color in the apical area. Damon Q2 has the most minimal stress or is indicated by the distribution of blue compared to all brackets.

Table 2. Tooth and PDL stress distribution result of Edgewise, Roth, MBT, Damon Q1, Damon Q2 Bracket.

Bracket type	Tooth Stress Distribution (MPa)		PDL Stress Distribution (MPa)	
	Maximum	**Minimum**	**Maximum**	**Minimum**
Edgewise Bracket	0.91242	0.15692	0.50487	0.12223
Roth Bracket	0.94247	0.18665	0.53216	0.12884
MBT Bracket	0.95613	0.20317	0.55263	0.13379
Damon Q1 Bracket	0.98345	0.20977	0.57992	0.14040
Damon Q2 Bracket	0.99984	0.21308	0.59765	0.14469

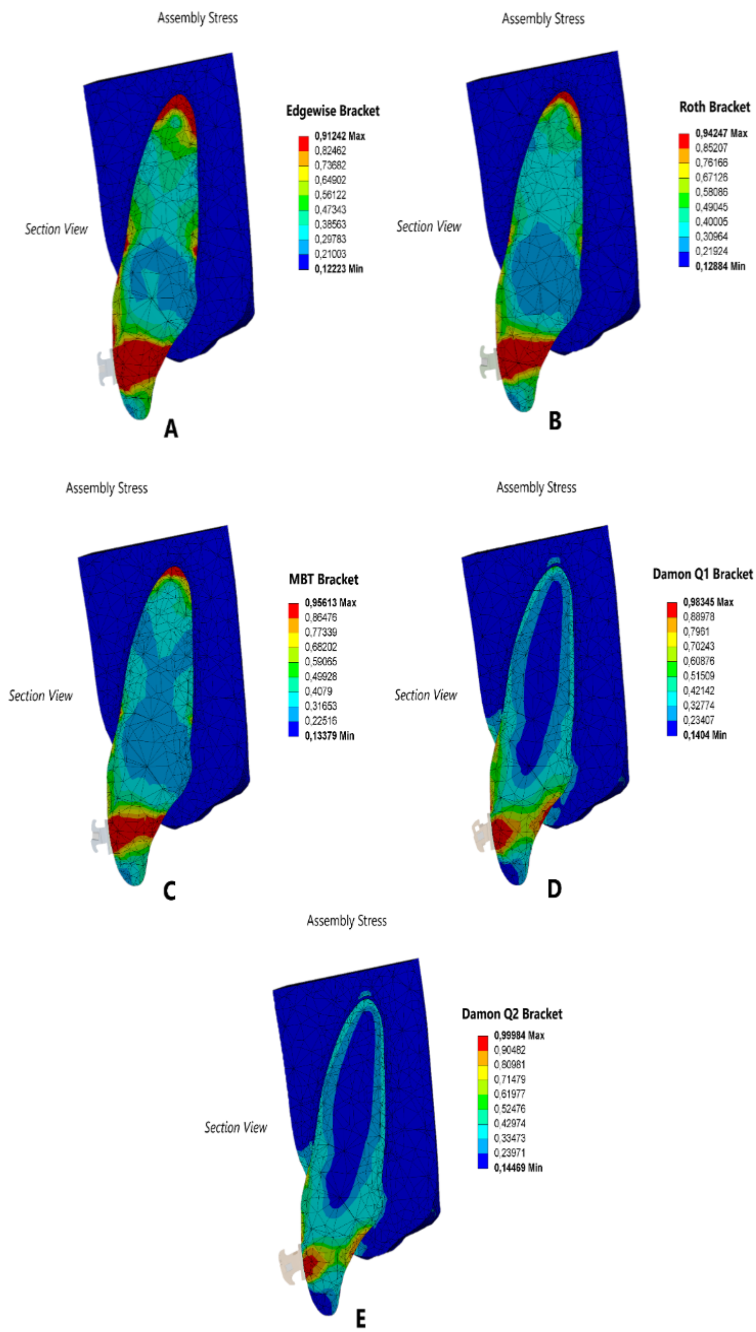

Figure 3. Assembly Stress Distribution Result (A) Edgewise Bracket, (B) Roth Bracket, (C) MBT Bracket, (D) Damon Q1 Bracket, (E) Damon Q2 Bracket.

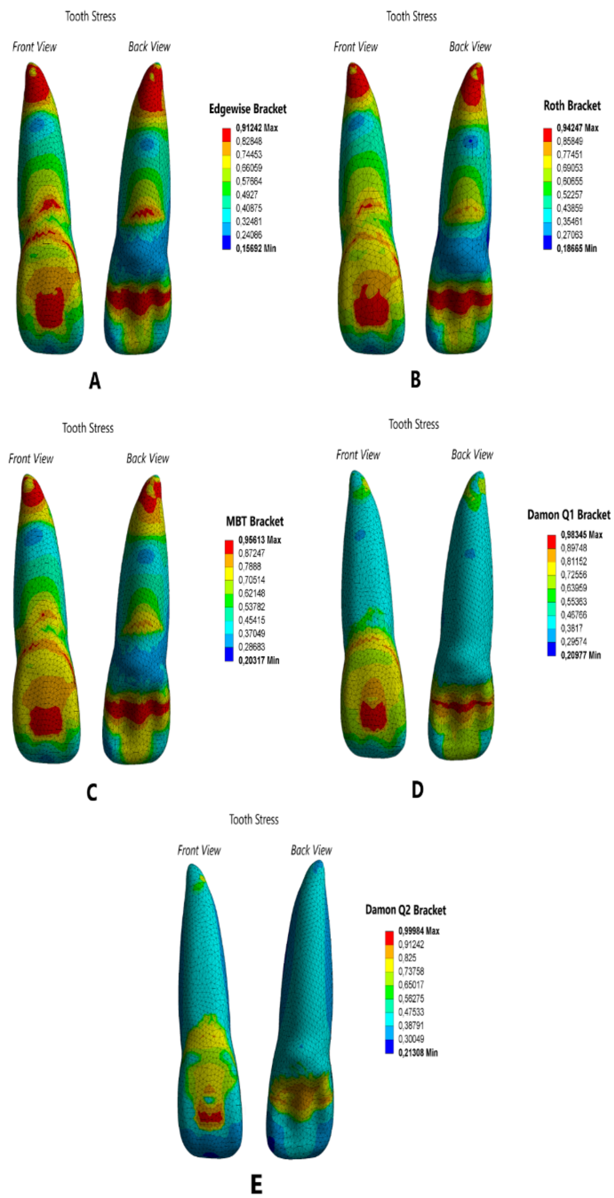

Figure 4. Tooth Stress Distribution Result With (A) Edgewise Bracket, (B) Roth Bracket, (C) MBT Bracket, (D) Damon Q1 Bracket, (E) Damon Q2 Bracke.

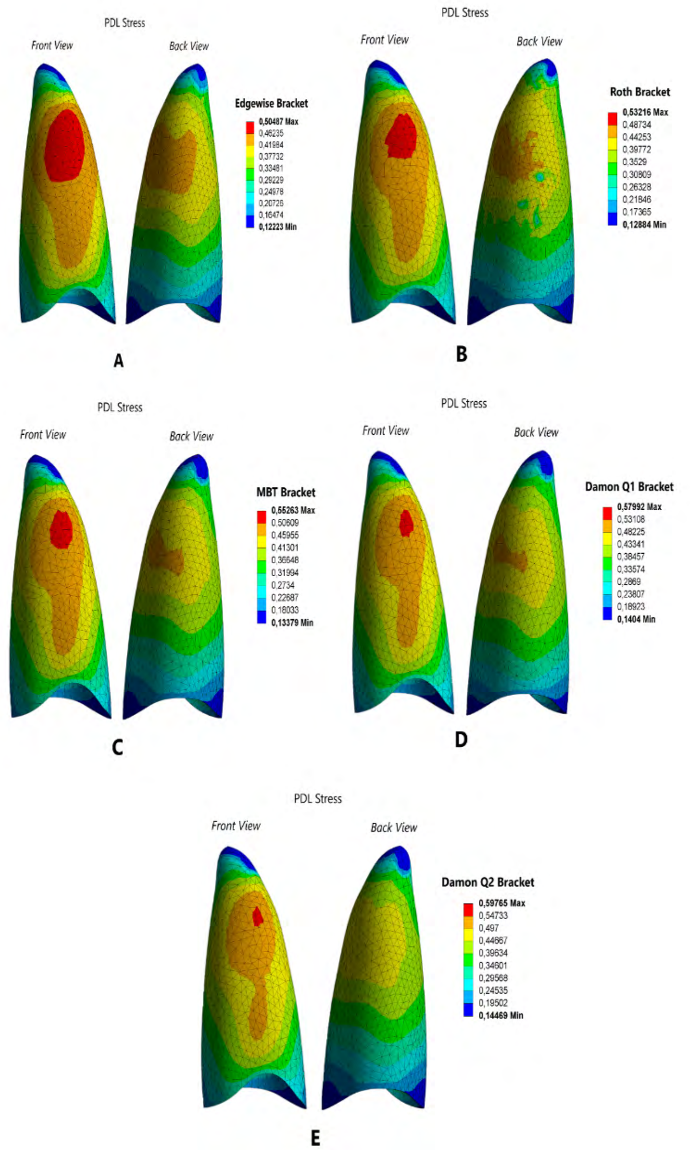

Figure 5. PDL Stress Distribution Result With (A) Edgewise Bracket, (B) Roth Bracket, (C) MBT Bracket, (D) Damon Q1 Bracket, (E) Damon Q2 Bracket.

DISCUSSION

Finite element analysis was utilized in this research due to the intricacy of the clinical design, diversity in dental characteristics, the multitude of elements requiring alignment, and the myriad factors influencing tooth movement. The FEA approach provides a non-invasive technique to model the mechanical response of the tooth and adjacent tissues, facilitating an in-depth evaluation of the stress distribution patterns produced by different orthodontic bracket systems (10). While FEA offers significant insights into biomechanical phenomena, it is crucial to recognize that this method cannot completely emulate the complex biological processes inherent in clinical orthodontic treatment. The simulation does not take into account differences between patients, how tissues respond over time, or how teeth, bone, and periodontal ligaments interact with each other in an intricate manner. The maxillary central incisors were chosen because to their visibility during talking and smiling. The maxillary incisors are essential for establishing anterior guidance and an aesthetically pleasing smile line (11). This study presents varying stress outcomes associated with the edgewise, Roth, MBT, Self-ligating Damon Q1, and Self-ligating Damon Q2 Bracket.

The findings indicate a significant difference in stress distribution between the different bracket systems. The edgewise bracket showed that stress was not evenly distributed out, with the crown and root areas having the most stress. This finding aligns with prior research that has underscored the drawbacks of conventional edgewise brackets, which frequently result in localized stress and may induce unfavorable dental movements, such as tipping. This is especially important because the edgewise bracket system depends on manual wire adjustments to control tooth movement, which can cause inconsistent torque expression if not done precisely. As previous research indicates, this deficiency in torque control may lead to ineffective or potentially detrimental movements of the tooth, including root resorption and uncontrolled tipping (12,13).

The Roth and MBT brackets have essentially comparable patterns; however, the size of the red region is reduced on the Roth and even more so on the MBT. This study utilized 0.22" slot MBT brackets and Roth brackets, as these represent the most prevalent prescriptions. A survey indicates that 52.6% of orthodontists like MBT brackets, whereas 44% prefer Roth brackets (14). Roth brackets are recognized for their accuracy and focus on the excessive correction of deep bites. These findings correspond with the design of the Roth system, which employs greater forces resulting in substantial vertical and anteroposterior movement. This approach is frequently favored when the primary objective is the repair of deep bite. Conversely, the MBT system, engineered to exert lesser forces for more gradual tooth movement, exhibited more conservative results (15). An MBT prescription for an extraction case that requires retraction is precisely designed to offer controlled tipping and torque, especially for the maxillary incisors. This prevents the incisors from tipping too far back (lingual inclination) and allows for effective space closure while retaining an attractive appearance (16).

The self-ligating Damon Q1 and Q2 brackets, on the other hand, showed a more even distribution of stress across the tooth and periodontal tissues. The color gradient maps from the FEA simulations demonstrated a seamless transfer of stress, with few high-intensity stress zones, and most stress values residing within the green spectrum-signifying typical, biologically acceptable levels. The results of this study support the hypothesis that self-ligating systems like Damon Q1 and Q2 spread forces more evenly and lower the chance of localized high-stress areas that could cause root resorption or other adverse effects. These findings corroborate prior studies indicating the possibility of diminished root resorption and enhanced clinical efficiency with self-ligating systems, attributed to their low-friction design (11).

Similar to previous study, both conventional and Damon Q brackets showed the largest Von Mises stresses in the lateral incisor and its root, which were localized in the middle third during tooth movement. Accelerated tooth movement was associated with lower forces rather than higher forces. Damon Q brackets produce consistent light forces that are within an appropriate range, minimizing sub-optimal and excessive forces, hence enhancing the efficiency and biological compatibility of tooth movement (17). Damon self-ligating brackets demonstrate enhanced efficiency relative to conventionally ligated brackets, with the self-ligating group correcting malocclusion 2.7 times more rapidly than conventional brackets (18).

Tooth movement is greatly affected by bracket-archwire friction. Physical parameters such as archwire and bracket materials and connection mechanism effect friction. Conventional ligated edgewise brackets have higher frictional resistance due to their elastomeric bracket-archwire connection. Several self-ligating bracket technologies reduce friction. Self-ligation eliminates the need for an elastomeric attachment and reduces archwire friction. Self-ligating brackets may engage archwires more reliably, requiring less chair-side help and accelerating archwire removal and ligation (5). This low-friction environment allows for the application of lesser forces while still facilitating effective tooth movement, which benefits periodontal health. Secondly, the meticulously designed bracket slot and enhanced torque regulation in the Damon system ensure that forces are applied with greater accuracy and alignment to the specified treatment goals. These design features diminish the necessity for considerable wire manipulation or torque adjustment, therefore reducing operator variability and improving the overall predictability of treatment results (11, 19).

The periodontal ligament (PDL) can trigger biochemical and cellular processes crucial for bone remodeling and allow orthodontic tooth movement. Evaluating alterations in tension and pressure within the periodontal ligament is essential for comprehending the biological dynamics of the dentoalveolar complex (20, 21). It has been shown that when excessive orthodontic force is applied to the tooth crown, resulting in pressure at the PDL that surpasses capillary pressure, capillaries may burst, leading to hyalinization and necrosis of the periodontal tissue, ultimately resulting in root resorption. Orthodontic force was observed to generate microcracks due to the combined compression stress and strain on the surface of the root. Prior research has established that microcracks in bone tissue induced by mechanical causes can stimulate osteoclast activity and are significantly associated with bone resorption (22). The Damon System operates on a system of applying a threshold force that is sufficiently low to prevent the occlusion of blood vessels in the PDL, thereby enabling the transport of cells and biochemical signals to the sites of bone resorption and apposition, thus promoting tooth movement (23).

The extent of root resorption was comparable amongst the groups, implying that the Damon self-ligating system would lessen root resorption. These claims were based on the assumption that low-friction appliances require minimal and consistent forces to mobilize the teeth, hence tending to biologically retain the periodontal ligament. The magnitude of the force did not seem to be a determining factor in the occurrence of root resorption (24, 25). Root resorption was found to be equivalent in self-ligating and conventional ligating brackets during the initial treatment phase, using CBCT, which provides improved imaging precision. Established that root resorption is comparable in self-ligating and conventional ligating brackets during the initial treatment phase, utilizing CBCT, which offers enhanced imaging precision (25, 26). Future comparison studies utilizing CBCT post-treatment completion should be conducted to validate the present findings. Another research indicated that increased forces led to significantly greater root resorption in comparison to lesser forces. Studies utilizing scanning electron microscopy (SEM) have demonstrated that root resorption is affected by both the duration and magnitude of the applied force, as well as the type of tooth movement (27).

This study provides useful insights into tooth and tissue stress distribution and mechanical response, but it has several limitations. First, the study simplified modelling by focusing on the maxillary central incisor. The study's single tooth type and alignment system may not properly represent orthodontic treatment's difficulties across varied patient profiles. Without patient-specific elements such tissue variability, responsiveness to stresses over time, and complicated interactions between teeth, bone, and periodontal ligaments, the results may not be clinically applicable. Second, the FEA technique predicts stress distribution well, but clinical observations and empirical data did not validate it. Since biological responses, patient compliance, and operator technique are hard to mimic in clinical settings, simulation alone raises concerns about prediction accuracy. Third, stress distribution-root resorption assumptions are simplified in the study. Without direct clinical confirmation using imaging techniques like CBCT or SEM, bracket systems' biological effects cannot be fully confirmed.

CONCLUSION

This finite element analysis underscores the biomechanical effects of bracket design on the tooth-periodontium complex. The self-ligating Damon Q1 and Q2 brackets provide superior stress distribution than the conventional bracket, resulting in a more balanced and physiologically advantageous force application. While these methods demonstrate potential advantages in minimizing unfavorable periodontal consequences, clinical extrapolations should be made with caution due to the study's limited scope. Further study with broader clinical validation and long-term follow-up is required to corroborate these findings. Nonetheless, the findings indicate that self-ligating brackets, such as the Damon system, may provide more predictable and efficient orthodontic treatment in appropriate clinical settings.

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CONFLICT OF INTEREST STATEMENT: The authors do not have any competing interest to report.

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