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Torque moments and stress analysis in two passive self-ligating brackets across different incisor inclinations: A 3-dimensional finite element study

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ABSTRACT

Objective: To compare torque expression characteristics between rectangular slot (0.022″ x 0.028″) Damon Q passive self-ligating brackets (Ormco, Glendora, Calif) and square slot (0.021″ x 0.021″) Pitts 21 brackets (OC Orthodontics) using 0.019″ x 0.025″ Stainless Steel and 0.020″ x 0.020" Titanium Molybdenum alloy wires at various incisal inclinations using finite element analysis. The null hypothesis was that there were no differences in torque expression in both tested groups.

Methods: Reporting guidelines for in-silico studies using finite element analysis in medicine (RIFEM) were used. Damon Q and Pitts 21 brackets were scanned and 3D models generated. Brackets were placed on a 3-D model of a maxillary central incisor with its long axis inclined at 0°,5°,10°,15° and 20° to the occlusal plane. Final 0.019″ x 0.025″ SS and 0.020″ x 0.020" TMA archwires were inserted into slots of both tested brackets. Geometric models were converted into finite element models. Material properties were assigned for involved structures with automatic meshing performed by software. Torque movements were simulated with the FE program Ansys Space claim R 22.

Results: Torque moment values, torque expression and Von - Mises stress was higher in Pitts 21 than Damon Q at all inclination angles. There was a gradual increase in the magnitude of values with decrease in incisal inclination.

Conclusion: Square slot passive self-ligating brackets show superior torque expression characteristics as compared to rectangular wire-rectangular slot combinations. The FEM results should be validated with in-vivo studies in order to confirm the findings.

1. Introduction

The field of orthodontics has witnessed significant advancements in recent years, characterized by an increased emphasis on optimizing treatment efficacy, enhancing patient comfort, and pursuing superior clinical outcomes. At the heart of this specialized discipline, fundamental biomechanical concepts, such as torque and tooth inclination, hold paramount importance in shaping the precision and effectiveness of orthodontic interventions. Torque refers to the rotational movement or torsion of a tooth along its longitudinal axis, thus dictating the angulation of the crown in relation to neighbouring teeth and the dental arch.[1] Conversely, tooth inclination denotes the angular orientation of a tooth relative to a vertical reference axis.[2] Both torque and tooth inclination are pivotal determinants in the meticulous planning and execution of orthodontic treatment, with direct implications for ultimate dental alignment, occlusal relationships, and overall aesthetic considerations of the dentition.

A substantial body of orthodontic research has been conducted to understand these biomechanical concepts. Several studies have examined the relationship between torque expression and the role of bracket slot size between 0.018″ and 0.022″ slots, some stating no significant difference between both sizes while some found higher torque expression in the 0.018″ slot.[3,4] Furthermore, previous investigations conducted in relation to tooth inclination and torque have predominantly focused on the 0.022" slot in both conventional and self-ligating brackets.[5–9] The primary conclusion of these studies is that the choice of prescription can guide the correction of incisal inclination, but the final position may not always align perfectly with it. The degree of change in inclination applied was the most important factor in predicting clinical results.

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The recent introduction of a square slot in labial passive self-ligating fixed orthodontic appliances has garnered significant attention within the field of orthodontics. The square slot design represents a departure from the traditional rectangular slot configuration typically used in orthodontic brackets. This square slot design offers certain advantages.[10,11] It provides a more precise and controlled mechanism for torque and tooth inclination adjustments during the course of orthodontic treatment. Early tip and torque control is facilitated due to the use of arch wires with a square cross section in a square slot which permits full slot engagement quickly in treatment. Variable modulus technology enables the use of softer full-size wires earlier in treatment enabling three-dimensional control. The square slot in labial passive self-ligation has not yet been studied. However, it has been stipulated that it provides for a better fit between the archwire and the bracket, resulting in improved engagement and, subsequently, more accurate torque expression to the teeth.[12]

Thus, this study aimed to compare the characteristics of torque expression between two types of passive self-ligating brackets, namely rectangular slot (0.022″ × 0.028″) Damon Q passive self-ligating brackets (Ormco, Glendora, USA) and square anterior slot (0.021″ × 0.021″) Pitts 21 brackets (OC Orthodontics, Oregon, USA) across different incisor inclinations using finite element models.

The null hypothesis for this study was that there were no differences in torque expression in rectangular slot and square slot SLBs on use of prescribed final archwires.

2. Methods

The study compared the torque expression of two passive self-ligating bracket systems: Damon Q and Pitts 21. In Damon Q, the archwire prescription for finishing was 0.019″x 0.025″ SS, while in Pitts 21, the manufacturer recommended 0.020″ x 0.020″ TMA. Previous studies have shown that there is insufficient torque expression in rectangular slot passive SLBs when using a final size 19 × 25 SS wire due to the large amount of play of approximately 11° in a 0.22″ bracket slot.[13] To overcome this deficiency, variable torque prescription brackets with enhanced torque values are needed in such systems. The newly introduced square passive SLB Pitts 21 system with slot dimensions of 0.021 × 0.21″ anteriorly supposedly overcomes this limitation by enabling complete filling of the slot when using a 0.20″ x 0.20″ TMA wire with reduced play of 4°, according to the manufacturer's claims. The Pitts 21 system utilizes the principles of variable modulus orthodontics as originally stated by Burstone,[14] who advocated the use of full-size wires early in treatment utilizing archwire alloys which were softer at the beginning of treatment and harder at the final stages to control the force magnitude. The study aimed to test and validate overall torque expression in rectangular and square slot systems, particularly in the anterior segment where inadequate torque expression is a common problem. In accordance with the reporting guidelines for in-silico studies using finite element analysis in medicine (RIFEM)[15] the methodology is as under.

2.1. Acquisition of image

Damon Q and Pitts 21 brackets were mounted on strips of modelling wax with radiolucent carbon tape which prevented the formation of artifacts during the scanning process.

The brackets were individually scanned using a micro computed tomography scanner (Skyscan 1217 Bruker, Belgium) in the Digital Imaging and Communication in Medicine format (DICOM) onto a compact drive for 45 mins with a total of 1000 slices per scan creating high-quality bracket models with all surface details. The DICOM files were then imported into Mimics Research 21.0 software where the data was converted into stereolithographic (STL) format.

2.2. Construction of finite element model

A 3D computer-aided designed (CAD) model obtained from Turbo Squid (Turbo Squid, New Orleans, USA) served as the base for geometric tooth construction. From this CAD model, modifications were made using Solid Works to alter tooth geometry according to dental anatomy literature. A 3D model of the maxillary central incisor was constructed from the CAD model surrounded uniformly by PDL 0.2 mm thick and alveolar bone crest 1 mm below the cementoenamel junction.[16]

The 3D models of brackets in STL format were then converted to solid models by exporting data to Ansys Space Claim R 22.0 software where cleanup and model checking was performed. The solid models were imported into Solid Works 2021 where models were recreated according to the actual bracket dimensions. Archwires were modeled and produced separately as 0.019″ x 0.025″ SS and 0.020″ x 0.020" TMA beam elements inserted passively into bracket slots (Fig. 1A and B).

The long axis of each incisor model was inclined 0°,5°,10°,15° and 20° to a line perpendicular to the occlusal plane. Brackets were attached at FA point onto the maxillary central incisor teeth models at these incisal inclinations with direct contact between the bracket base and tooth surface with no gap between them (Fig. 1G).

The geometric models were converted into finite element models.

2.3. Segmentation

Masking was done by capturing the required region using a masking tool in Mimics software with the use of Mimics Multiple Slice Edit segmentation tools to add or remove entities. Segmentation was done for both the bracket types.

2.4. Convergence test

Convergence tolerance for residual relative force = 0.1 and for the incremental rotations of rigid link nodes = 0.001 was used. A sensitivity analysis was done by subdividing all elements across all three dimensions to check the reliability of the existing mesh.

2.5. Total number of elements and nodes of the finite element model and the shape of each element

3D tetrahedral elements were used for discretizing the complete assembly. A total of 1885715 elements were connected by 647722 nodes for Damon Q and 333210 elements were connected by 65412 nodes for Pitts 21 brackets with element size of 0.75 mm in linear element order (Fig. 1C and D).

2.6. Assigning material properties

Material properties including Young's modulus and Poisson's ratio were assigned for teeth, periodontal ligament, alveolar bone, brackets and archwires used in the investigation, from values obtained from a previous study by Fercec et al. and Kanjanaouthai et al. (Table-1).[17,18]

The mechanical properties assigned to the elements were isotropic (having physical properties of the same values when measured in different directions) and linear elastic (linear relationships between the components of stress and strain). Ansys Mechanical R22.0 was then used for importing models with 0 % data loss. The software performed automatic meshing with defined material properties.

2.7. Boundary conditions

Boundary conditions or constraints were applied to the finite element model (Fig. 1E and F). Free body motion for the model was constrained by fixing all nodes at the base of the model (bone) in all directions. Nodes on mesial and distal surfaces of the bone section were fixed only in mesiodistal and inciso-apical directions, which allowed

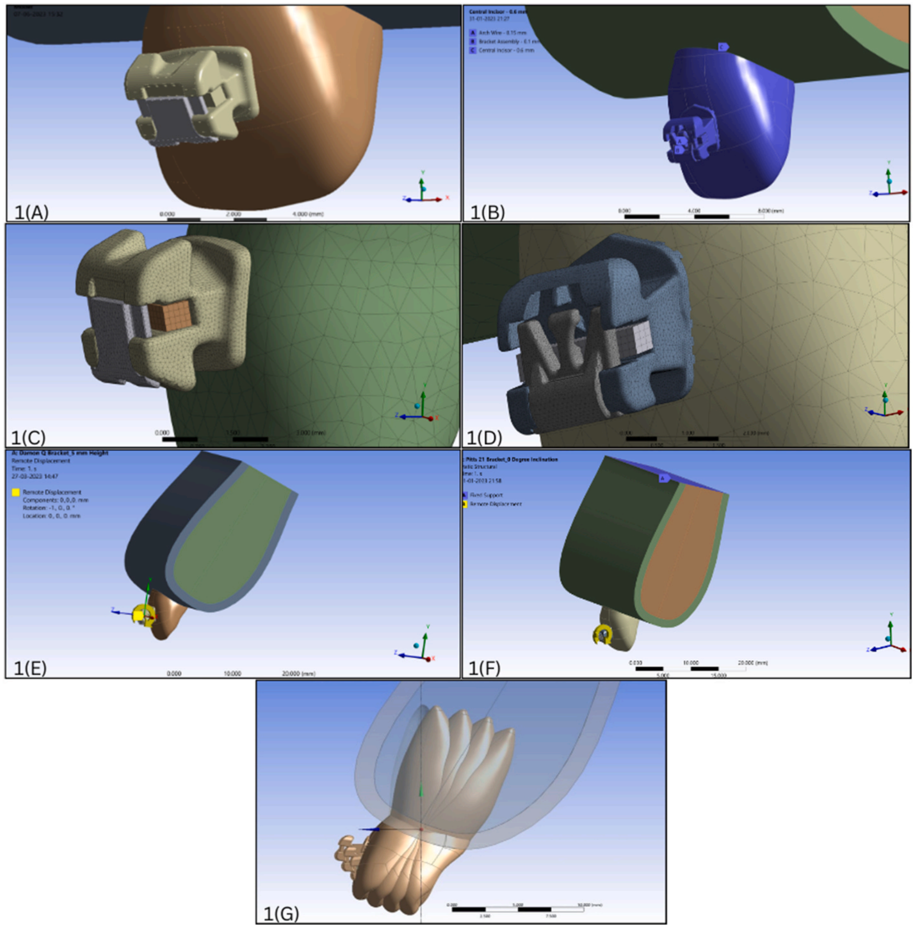

Fig. 1. Methodology: A) Solid model of Damon Q bracket with 0.019″x0.025″ SS wire, B) Solid model of Pitts 21 bracket with 0.020″x0.020″ TMA wire, C) Meshing of Damon Q bracket with nodes, D) Meshing of Pitts 21 bracket with nodes, E) Boundary conditions of Damon Q, F) Boundary conditions of Pitts 21, G) Bracket placed at different inclinations of maxillary central incisor.

Table 1
Average material property values.

S·NO.	Linear -elastic material parameters used	Young's modulus of elasticity, E (MPa)	Poisson's Ratio
1.	Teeth	20300	0.30
2.	Brackets	180000	0.3
3.	Titanium Molybdenum Archwire	86000	0.3
4.	Stainless steel	1.93E +0.5	0.3
5.	PDL	0.68	0.49
6.	Alveolar bone	13700	0.30

MPa-Megapascal.

bending of the bone in a labiolingual direction. The wire was allowed to move freely in bracket slots and wire deformation did not occur till contact with the walls of the bracket slots causing wire restriction.

2.8. Loading

A minimum twist of 1° was given for both archwires to observe and enable measurement of torquing moments at different inclinations.[19]

2.9. Interpretation of FEA

The coordinate system was constructed with x-axis depicting mesiodistal direction, the y-axis depicting vertical displacement and z-axis depicting anteroposterior direction. Simulations of the torque movement were performed with the FE program system Ansys Space claim R 22. The displacement changes in tip of the incisor after FE simulation was assessed along the z-axis. In both bracket types, torque moments generated on use of full-size wires were recorded. The results obtained were tabulated in the form of graphs.

3. Results

Simulation of torque moments was conducted using the ANSYS SPACE Claim R22 program on a 3D model of a maxillary central incisor tooth at various inclinations (0°, 5°, 10°, 15°, and 20°). Finishing archwires (0.019″ x 0.025″ SS and 0.020″ x 0.020" TMA) in their respective SLB prescription (Damon Q and Pitts 21) were twisted by 1° inside the bracket slot at different tooth inclinations following which observations were recorded as shown in Fig. 2 regarding torque moments, torque expression and Von-Mises stress (Table 2) and are as follows.

a) Comparison of torque moments between Damon Q and Pitts 21 SLBs at different inclinations (0°,5°,20°,15°,20°)

Torquing moments generated by two passive self-ligating brackets (Damon Q and Pitts 21) were recorded at different inclinations (0°, 5°, 10°, 15°, and 20°) using their respective finishing wires (0.019″ x 0.025″ SS and 0.020″ x 0.020" TMA). The results revealed that, across all inclinations, both passive self-ligating brackets exhibited the highest torquing moment at 0° inclination and the lowest at 20° inclination.

Square slot Pitts 21 consistently demonstrated a higher torquing moment than Damon Q at all inclinations studied. Specifically, at

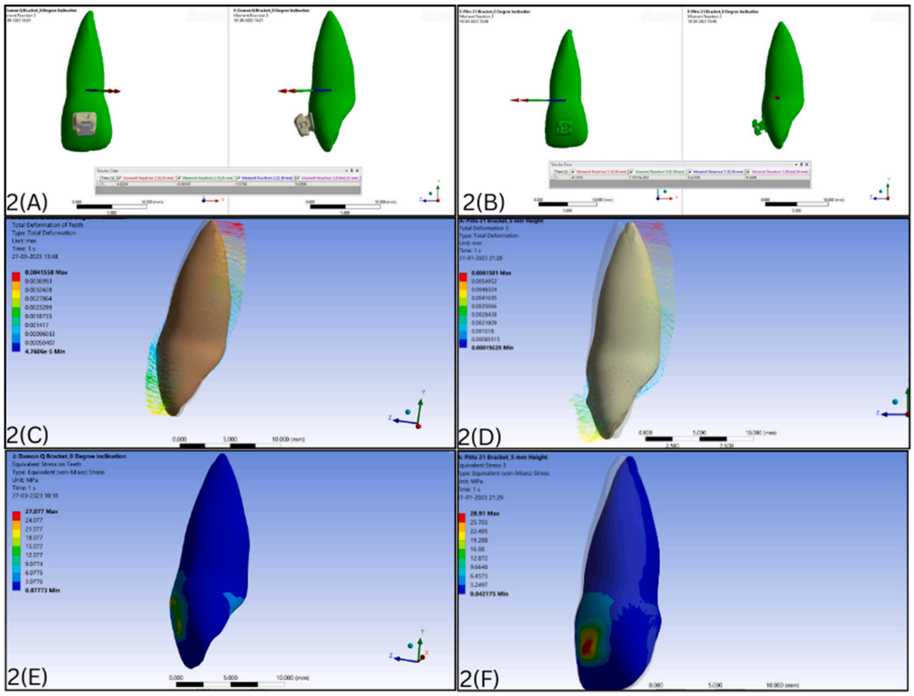

Fig. 2. Assessment: A) Torque moment in Damon Q, B) Torque moment in Pitts 21, C) Total deformation in Damon, D) Total deformation in Pitts 21, E) Von -Mises Stress in Damon Q, F) Von -Mises Stress in Pitts 21.

Table 2
Torque moment, total deformation and stress generated by Damon Q and Pitts 21 bracket.

Incisal Inclination	Moment (N-mm)		Total deformation (mm)		Von mises stress (MPa)	
	Damon Q Bracket	Pitts 21 Bracket	Damon Q Bracket	Pitts 21 Bracket	Damon Q Bracket	Pitts 21 Bracket
0°	9.0398	9.14	0.0041558	0.0061581	27.077	28.91
5°	8.3579	9.12	0.0037402	0.0058181	26.707	28.84
10°	7.7479	7.942	0.0035324	0.0056103	25.567	26.229
15°	6.9396	7.4444	0.0033246	0.0054025	23.362	25.438
20°	6.6617	6.7616	0.0031168	0.0051947	20.458	22.068

N-mm:Newton-millimeter, mm:millimeter, MPa:Megapascal.

0° inclination, Pitts 21 exhibited the maximum torquing moment, measuring 9.14 N-mm. In contrast, Damon Q recorded a maximum torquing moment of 9.03N-mm at the same inclination. Conversely, at 20° inclination, Pitts 21 displayed the minimum torquing moment, measuring 6.76 N-mm. In comparison, Damon Q recorded a minimum torquing moment of 6.66 N-mm at the corresponding 20° inclination as evident in Fig. 3.

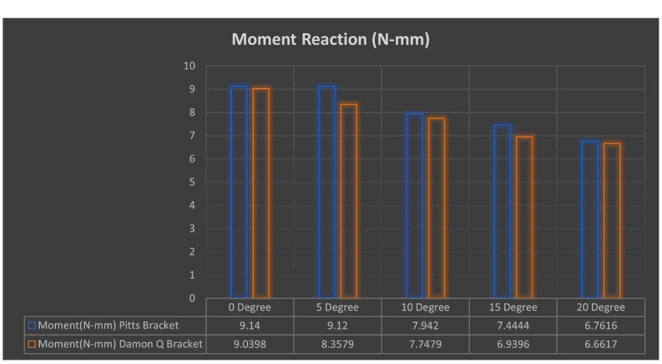

Fig. 3. Comparison of torque moments between Damon Q and Pitts 21 at different incisal inclinations.

b) Comparison of total deformation (tooth movement) by Damon Q and Pitts 21 SLBs at different inclinations (0°,5°,20°,15°,20°)

In the context of finite element analysis, tooth deformation refers to changes in the shape and position of teeth under different conditions and forces.[20] Our study aimed to measure the total deformation of the central incisor by applying a one-degree twist to the finishing archwires of both Damon Q and Pitts 21 brackets. We recorded these measurements in all axes (x, y, and z), and calculated the net value for each inclination for both brackets. Our results showed that both passive SLBs had a similar pattern, with the maximum deformation observed at 0° and the minimum at 20°. However, the total deformation was significantly higher with the Pitts 21 bracket than with the Damon Q bracket at all incisal inclinations as seen in Fig. 4. For instance, at 0°, the Pitts 21 bracket recorded 0.006 mm tooth deformation, while the Damon Q bracket recorded 0.004 mm tooth deformation. Similarly, at 20°, the Pitts 21 bracket recorded 0.005 mm tooth deformation, whereas the Damon Q bracket recorded 0.003 mm tooth deformation. Moreover, we observed that for both SLBs, the net movement of the root was more pronounced than that of the crown.

c) Comparison of Von-Mises's stress by Damon Q and Pitts 21 SLBs at different inclinations (0°,5°,10°,15°,20°).

The Von Mises stress is a scalar value derived from the three principal

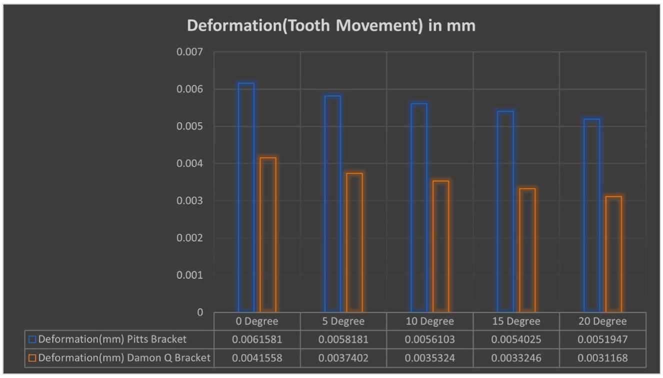

Fig. 4. Comparison of total deformation (tooth movement) with Damon Q and Pitts 21 at different inclinations.

stresses in a material, commonly employed to predict material yield under complex loading conditions.[21] In the context of applying torsional stress by twisting the finishing archwires within their respective passive self-ligating brackets (Damon Q and Pitts21), Von Mises stress values were extracted at each element of the bracket, wire, and tooth, and the net stress was then calculated.

Recorded Von Mises stress was observed on the labial surface of the central incisor at the bracket-tooth interface for both Damon Q and Pitts21 passive self-ligating brackets. The maximum value was recorded at a 0° inclination, measuring 28.01 MPa for Pitts 21 and 27.07 MPa for Damon Q, while the minimum values at 0° inclination were 22.06 MPa for Pitts 21 and 20.45 MPa for Damon Q. Upon comparing both Pitts 21 and Damon Q self-ligating brackets, it was evident that Pitts 21 exhibited higher Von Mises stresses than Damon Q (Fig. 5).

4. Discussion

The present study was conducted to analyse torque moments and stress distribution patterns in rectangular (Damon Q) and square slot (Pitts 21) passive self-ligating brackets across different incisor inclinations using finite element method. The findings of this research offer valuable insights into the biomechanical performance of these two bracket systems.

The results of our investigation demonstrated a consistent increase in torque moment values for both Damon Q and Pitts 21 brackets as the degree of tooth inclination decreased (proclined to upright incisors). This trend aligns with established biomechanical principles, indicating that greater torque is required to correct teeth with more significant inclinations. Notably, our study revealed that Pitts 21 brackets with square anterior slots consistently generated higher torque moment values as compared to Damon Q bracket with rectangular slot across all

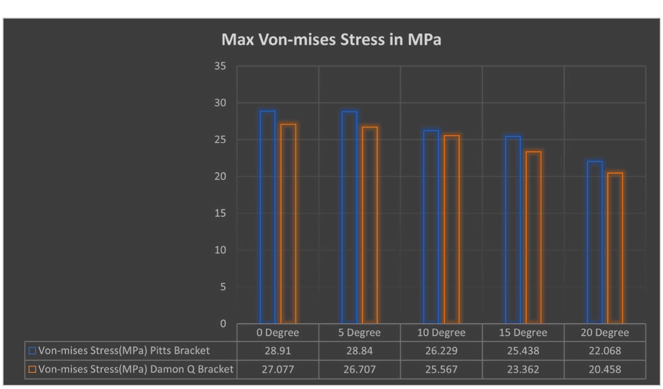

Fig. 5. Comparison of Von-Mises stress between Damon Q and Pitts 21 at different incisal inclinations.

inclinations. The higher torque moment values associated with Pitts 21 brackets suggest that they offer superior torque control, making them particularly suitable for orthodontic treatment that involve the correction of teeth with considerable inclinations. This could be attributed to the square slot design of 0.021″ x 0.021″ anteriorly, which provides a more precise and controlled mechanism for torque adjustments on the use of 0.020″ x 0.020" archwires. Our study also examined torque expression, which represents the efficiency of transferring torque from the archwire to the teeth. The results indicated that similar to torque moments, the values for torque expression were consistently higher with Pitts 21 brackets compared to Damon Q brackets at each level of tooth inclination. This suggests that the square slot design in Pitts 21 brackets enables more accurate and efficient torque expression. This is in accordance with studies conducted on square slots in lingual orthodontic appliances to assess torque moment generation and torque expression.[10,11,22] While previous studies on torque moments and expression have focused on pre-treatment and post-treatment values for teeth in digital models, using a tooth coordinate system, our study utilized a more comprehensive finite element analysis approach. This allowed us to examine the torque characteristics of these brackets in a controlled environment, providing a more precise assessment of their biomechanical performance via simulation. Moreover, FEM enables prediction of the behaviour of biological structures involved in the specific situations of our study. Measurements that cannot be taken in vivo, may contribute useful information to clinical investigations, thus FEM is considered in our study. Our study uniquely contributes to this area as it is the first to evaluate torque expression between square and rectangular slot brackets in a labial orthodontic appliance.

On examination of previously published literature on torque, Dalstra et al. found that the actual torsional play in bracket systems, especially passive self-ligating brackets, was larger than anticipated. This play ranged from 19.80° to 36.10° between conventional and self-ligating brackets in 0.022" slots. They concluded that self-ligating brackets, particularly passive self-ligating brackets with 0.022 slots, did not favour torque control due to the larger actual play caused by oversized slots and the inability to press the archwire into the bottom of the slot.[23] Similar results were shown in a study conducted by Morina et al.[24] However, a study by Thushar et al. compared torque expression between passive and active self-ligating bracket systems and concluded that passive self-ligating brackets, such as Damon Q, exhibited superior torquing characteristics compared to active self-ligating brackets with similar archwires.[25] The variation in results is likely due to the equipment used for torque measurement: previous studies employed orthodontic measurement and simulation system (OMSS), while Thushar et al. used FEM.

The analysis of Von-Mises stress distribution in Damon Q and Pitts 21 brackets revealed that both brackets exhibited increased stress levels as the degree of tooth inclination decreased. This observation is consistent with the understanding that teeth with greater inclinations require higher forces to correct, resulting in greater stress concentrations around the brackets as seen in FEM studies conducted by Papageorgiou et al. and Kanjanaouthai et al.[18,26] It is important to note that there were no significant differences in Von-Mises stress patterns between the two bracket types. In both cases, Von Mises stress was concentrated around the brackets. This indicates that the square slot design of Pitts 21 brackets did not significantly alter stress distribution patterns when compared to rectangular slot Damon Q brackets. The similar stress distribution patterns suggest that both bracket types can withstand the mechanical demands of orthodontic treatment, even in cases of significant tooth inclination.

Torque can effectively address axial misalignment, especially in the anterior teeth, by transmitting it through brackets using rectangular or square wires. Various tools and procedures, such as cephalometric measurements, intraoral measurements, and analysis of digitized models or intraoral scans, have been proposed to measure the axial angulation of teeth.[27] Savoldi et al. assessed the impact of different prescriptions on maxillary and mandibular incisor inclination using passive self-ligating brackets. Their findings underscored that the choice of bracket prescription is influenced by the initial dental inclination and inter canine distance, with the initial inclination being the pivotal factor for prescription selection.[28] Consequently, the present study integrated torque expression assessment with changes in tooth inclination measured through finite element analysis.

In a separate investigation, Monatasser et al. explored changes in crown inclination during orthodontic levelling and alignment with various archwire-bracket-ligation combinations. Their conclusion emphasized that all combinations led to lingual crown inclination, with conventional brackets ligated with elastomeric rings causing less pronounced changes. The consistent negative (−) values indicated a persistent trend towards lingual or palatal crown movements, aligning with the results of the present study.[6]

However, a retrospective study by Sfondrini et al. compared buccolingual inclination control of upper incisors among patients treated with conventional brackets, self-ligating appliances, and aligners, revealing no significant differences in buccolingual inclination control between the three treatment modalities.[5] This disparity may be attributed to the radiographic measurement of inclination. Thus, despite similar built-in tip and torque values for Damon and Pitts 21, Pitts 21 with 0.020″ x 0.020″ TMA archwires demonstrates better torque expression than Damon Q used with 0.019″ x 0.025'' SS archwire.

The study does have some limitations we should be aware of. Firstly, using computer models (FEM) often requires simplifying orthodontic bracket designs for computational ease, potentially not capturing their full clinical complexity.

Using micro-CT scanning techniques for obtaining bracket dimensions, geometry and configuration helps to improve the reliability of the generated FE models but inaccuracies may still affect the findings.

Secondly, these models are generic and don't account for individual patient differences in anatomy and physiology, which can influence real-world orthodontic outcomes beyond model predictions. Therefore, in vivo validation is vital in FEM to ensure that computer-based findings align with actual patient responses, addressing unaccounted-for variations.

5. Conclusion

In summary, the findings from this study suggest that square slot Pitts 21 brackets may offer advantages over rectangular slot Damon Q brackets in terms of torque moments and torque expression at variable incisor inclinations. Full archwire engagement in the slot provides early torque control in Pitts 21 brackets which can be utilized in patients requiring correction in axial inclination. The geometry of the square bracket and square archwire allows a tighter fit with reduced play which contributes to a higher degree of torque expression in these systems. However, it should be understood that results from FEM studies do not mimic in-vivo conditions. It is recommended that the findings of this study be corroborated with clinical studies to ratify the results. These results, however, contribute to our understanding of the mechanical behaviour of these brackets and archwires and clinicians can utilize the findings to achieve optimal outcomes.

Ethical approval

Not Applicable.

Consent to participate and consent for publication

Not Applicable.

Availability of supporting data

The data sets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Funding or sources of support

No funding/grant was provided for the research.

Ethical clearance

Ethical clearance for the study was obtained.

Patient consent

Ethical clearance not applicable as it is a FEM study.

Sources of funding

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Declaration of competing interest

The authors have no conflicts of interest to disclose.

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