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Comparative study of torque expression and its biomechanical effects: spherical self-ligating bracket with lock-hook system versus passive self-ligating bracket and conventional bracket

Yudong Liu[1†], Longmei Guo[1†], Yanqing Feng[1], Jiahao Hua[2], Qingyuan Dai[2], Ziyang Chen[4], Wenlu Song[4], Bing Guo[1*], Taicong Chen[2,3*] and Li Ji[1*]

Abstract

Background Proper torque control is crucial to the outcome of orthodontic treatment. This study aimed to employ finite element analysis to compare the torque capabilities of a novel spherical self-ligating bracket with a lock-hook system against those of commonly used passive self-ligating and conventional bracket systems, as well as to reveal the biomechanical changes in the periodontal ligament (PDL) during torque expression.

Methods A maxillary right central incisor, along with its PDL and alveolar bone, were modeled. Three types of brackets were selected: a spherical self-ligating bracket with a lock-hook system, a passive self-ligating bracket (Damon), and a conventional bracket (Discovery). Each bracket was equipped with a 0.022-inch slot and a 0.019 × 0.025-inch stainless steel archwire. A palatal root torque of 20° was applied. The torque moment, as well as the von Mises stress and strain in the PDL, were calculated. A clinical case involving the lingual inclination of the upper anterior teeth was utilized to assess the feasibility of using the spherical self-ligating bracket with the lock-hook system to express torque.

Results At a twist angle of 20°, the maximum torque generated by the spherical self-ligating bracket with a lock-hook system (27.8 N·mm) was approximately 1.6 times greater than that of the Damon bracket (17.5 N·mm) and the Discovery bracket (17.3 N·mm). As the twist angle increased, both the von Mises stress and the strain in the PDL also increased. When the maximum PDL stress was less than 0.026 MPa and the percentage of the PDL good strain area

†Yudong Liu and Longmei Guo contributed equally to this work.

*Correspondence:
Bing Guo
guobing@mail.sysu.edu.cn
Taicong Chen
cvchentc@scut.edu.cn
Li Ji
orthodentist_jili@163.com

Full list of author information is available at the end of the article

(defined as the area with PDL strain ≥ 0.3%) exceeded 50%, the torque range for the maxillary incisor was between 10.2 and 17.5 N·mm. The clinical case demonstrated that the use of the spherical self-ligating bracket with the lock-hook system effectively corrected the unfavorable linguoclination of the maxillary incisors.

Conclusions The spherical self-ligating bracket with a lock-hook system can significantly enhance torque expression. The optimal torque range for the maxillary incisor is between 10.2 and 17.5 N·mm.

Keywords Torque expression, Spherical self-ligating bracket, Lock-hook system, Biomechanics, Finite element analysis

Introduction

Proper torque control is essential for achieving optimal occlusal and aesthetic outcomes in orthodontic treatment. Although the straight wire appliance eliminates the need for third-order wire bending through preadjusted torque, the effectiveness of the bracket's torque expression is subject to various factors [1]. To ensure the precise expression of these prescriptions, full-size archwires are recommended to fill the bracket slots. However, the high friction and limited flexibility of these archwires have restricted their clinical application. Smaller archwires are often necessary to facilitate engagement [2], but achieving an intimate fit is rarely possible due to inconsistent contact between the bracket slots and the archwires. This inconsistency necessitates twisting the archwires to a specific angle, known as torsional play, to initiate torque expression. Excessive torsional play can lead to substantial torque loss, resulting in improper root positioning, extended treatment duration, and an increased risk of relapse [3].

Orthodontists have faced the critical challenge of achieving proper torque control. In clinical practice, supplementary devices, including auxiliary arches, are commonly employed to adjust torque, yielding satisfactory outcomes [4]. However, the use of these auxiliary devices is often complex and heavily reliant on the orthodontist's expertise and proficiency. To achieve effective and straightforward torque control, a novel orthodontic appliance was proposed: the spherical self-ligating bracket equipped with a lock-hook system (Patent No: US14/983193). This appliance has been utilized in orthodontic treatment and has garnered the attention of many orthodontists. In contrast to traditional square-shaped brackets, the spherical self-ligating bracket features a smooth, hemispherical curved design that reduces mechanical stimulation to the oral mucosa and minimizes the food retention. Notably, the bracket incorporates unique lock-hook system with a micron-sized threaded hole and a stainless steel (SS) lock screw. It is claimed that the archwire will be securely constrained within the slot when the lock screw is inserted into the threaded hole [5]. However, the torque capability of the spherical self-ligating bracket with the lock-hook system has not been thoroughly explored. Furthermore, research has demonstrated that increased torque can raise pressure associated with root resorption [6]. The critical mechanical stimulus that triggers the biological reactions leading to root resorption is the magnitude of stress within the periodontal ligament (PDL) [7, 8]. Therefore, it is essential to carefully monitor the biomechanical changes in the PDL during torque expression.

Due to the challenges associated with in vivo measurement, the torque expression of brackets and the corresponding biological changes must be analyzed using auxiliary tools. Finite Element Analysis (FEA) is a numerical analysis technique that facilitates non-invasive and reproducible investigations of the mechanical responses of various materials, including living tissues. It has found extensive application in orthodontics, such as in the study of stress−strain and displacement patterns of dentofacial tissues under applied loads [9], the determination of the center of resistance [10], the mechanical analysis of microimplant anchorage [11], and the biomechanical comparison of orthodontic appliances [12]. With advancements in digital imaging systems and iterations of computer software, researchers can design appropriate models based on various clinical scenarios for finite element biomechanical simulations. This allows for accurate, safe, economical, and efficient assessments of orthodontic appliance performance, optimization of treatment protocols, and prediction of treatment outcomes. Currently, research utilizing FEA on the novel spherical self-ligating bracket with the lock-hook system is limited. Therefore, this study aims to employ FEA to compare the torque expression of the spherical self-ligating bracket with the lock-hook system to that of the commonly used passive self-ligating bracket (Damon) and conventional bracket (Discovery). The goal is to evaluate whether the spherical self-ligating bracket with the lock-hook system exhibits superior torque capability compared to the other two brackets. Additionally, the biomechanical changes associated with torque expression were investigated to provide a theoretical framework for determining the appropriate torque range in clinical practice.

Materials and methods

Finite element modeling

A 20-year-old female with no dental caries, no dentition defects or edentulism, normal occlusion, a Class I molar relationship, and no periodontal or systemic diseases was selected for this study. Her dental and jawbone information was obtained using cone beam computed tomography (CBCT) and an intraoral scanner. The data from the scans were imported into the Mimics software (Materialise, Leuven, Belgium) in DICOM format for reconstruction. Three-dimensional models of the maxillary dentition and maxilla were generated through image preprocessing, threshold adjustment, region growing, mask editing, and Boolean subtraction. The maxillary right central incisor and its corresponding alveolar bone were selected and exported as STL files. These STL files were then imported into Geomagic Studio (Geomagic, North Carolina, USA) for reverse engineering reconstruction, where the models were optimized through smoothing, denoising, meshing, and surface fitting. The root of the maxillary right incisor was manually isolated 1.0–1.5 mm below the cementoenamel junction and then expanded outward by 0.20 mm to reconstruct the periodontal ligament (PDL). A spherical self-ligating bracket (OO Dental, Guangzhou, China), a passive self-ligating bracket (Damon, Ormco, Glendora, Calif), and a conventional bracket (Discovery, Dentaurum, Ispringen, Germany) were utilized in this study, all featuring 0.022-inch slots. Each bracket, equipped with an adhesive layer (mean thickness of 0.2 mm), was designed using SolidWorks 16.0 (SolidWorks Corporation, Velizy-Villacoublay, France), and bonded to the labial crown center of the incisor. A 0.019×0.025-inch SS archwire, measuring 8 mm in length, was passively inserted into each bracket slot. The spherical self-ligating bracket included a micron-threaded hole on the gingival side. When a lock screw was placed in the threaded hole, the archwire was secured in the slot with play elimination (Fig. 1) [5]. The Damon bracket restrained the archwire with a sliding door, while the Discovery bracket limited the archwire's movement with a 0.2 mm ligature (Fig. 2). Finite element models were established in Ansys Workbench 17.0 (ANSYS, Cononsburg PA, USA), with each bracket system having node-to-node connections to the adhesive, tooth, PDL, and alveolar bone (Fig. 2). The X-axis was oriented sagittally and was positive in the labial direction, the Y-axis was oriented vertically and was positive in the gingival direction, and the Z-axis was oriented horizontally and was positive in the distal direction.

Material properties

In this study, a third-order Ogden model was employed to assess the nonlinear hyperelastic properties of the PDL [13, 14]:

$$W = \sum_{i=1}^{N}\left[\frac{2\mu_i}{\alpha_i^2}\left(\bar{\lambda}_1^{\alpha_i}+\bar{\lambda}_2^{\alpha_i}+\bar{\lambda}_3^{\alpha_i}-3\right)+\frac{1}{D_i}(\mathrm{J}-1)^{2i}\right] \quad (1)$$

where W is the strain energy and N is the number of orders (N=3). The principal elongation $\bar{\lambda}_1$, $\bar{\lambda}_2$, $\bar{\lambda}_3$ and the volume change rate J are variables, and the material parameters μ_i and α_i and the incompressible parameter D_i are constants (μ_1=2.3 MPa, α_1=5.5, μ_2=0.0116 MPa, α_2=25, μ_3=2.55 MPa, α_3=4).

Other materials were considered homogenous and isotropic [15, 16]. The material properties are listed in Table 1. Notably, the parameters for the SS archwire and ligature were evaluated. A tensile test was conducted using six specimens of the archwires and ligatures in a universal testing machine [17]. The crosshead speed was set at 1 mm/min, and the gauge length of the wires was 40 mm. The Young's modulus was calculated from the load-deflection data obtained during the tensile testing.

Mesh

To ensure accuracy and computational efficiency, a second-order hexahedral element type was selected for the tooth, PDL and alveolar bone, while a linear tetrahedral element type was chosen for the remaining components.

Fig. 1 Design of the spherical self-ligating bracket with the lock-hook system

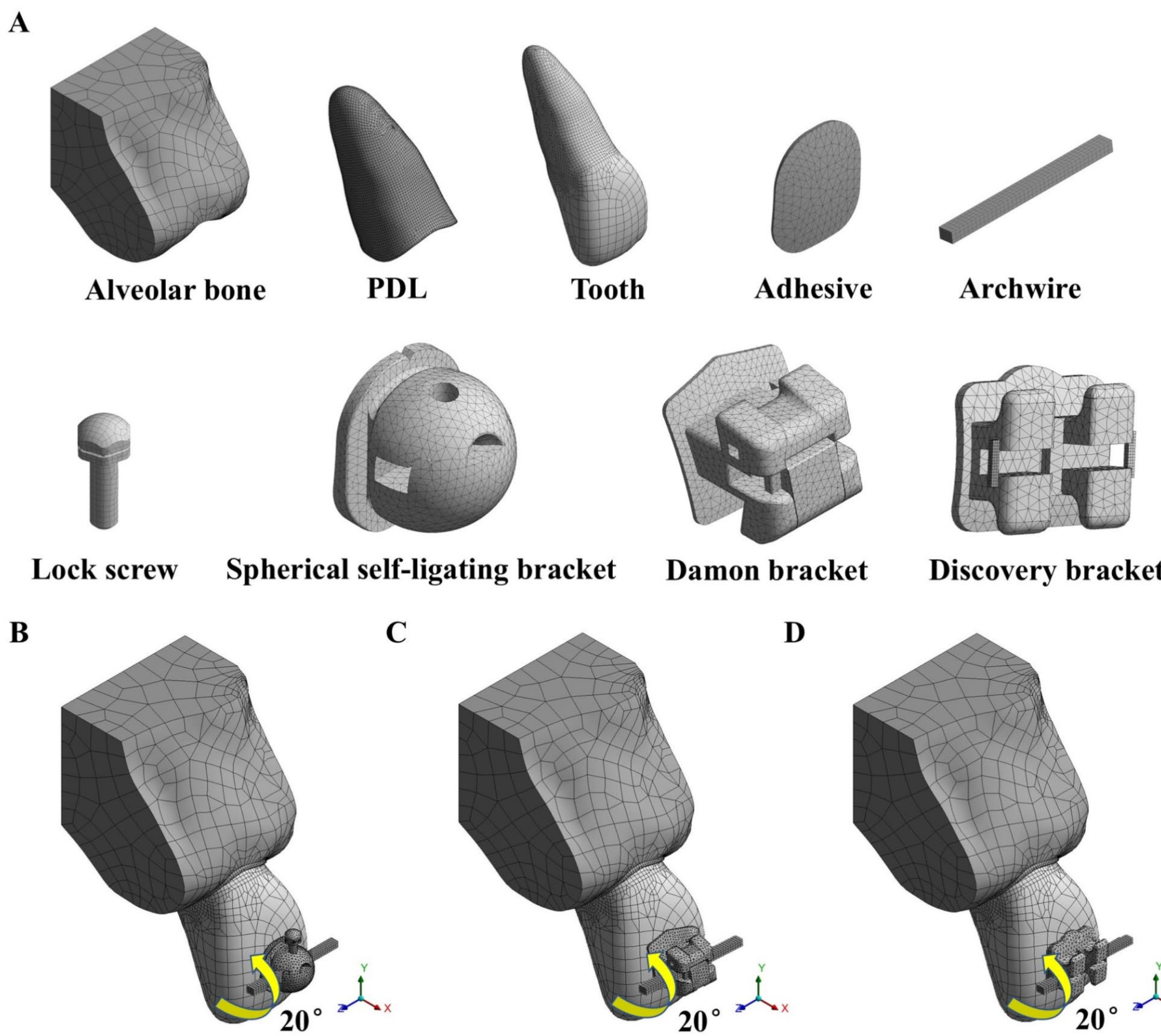

Fig. 2 Models used in the present study. (**A**) Geometric models, (**B**) finite element model of the spherical self-ligating bracket with the lock-hook system during torque expression, (**C**) finite element model of the Damon bracket during torque expression and (**D**) finite element model of the Discovery bracket during torque expression

The mesh convergence error values were less than 5% of difference between the results. Table 1 shows the number of elements and nodes for the analysis.

Boundary conditions

The connections between the bracket and archwire, the lock screw and archwire, and the ligature and archwire were defined as frictional contacts with a frictional coefficient of 0.2. The outer surface of the alveolar bone was designated as a fixed constraint to restrict its movement. A coordinate system was established at the intersection of the labial, mesial, and lingual surfaces of the maxillary right central incisor.

Loading method

The simulation was designed to replicate a palatal root torque of 20° acting on the incisor. Torque was applied at both ends of the archwire, resulting in a counterclockwise rotation along the axis of the archwire (Fig. 2). The torque moment values generated by various brackets at different angles of twist, as well as the von Mises stress and equivalent strain in the PDL, were calculated during the simulation.

Application to clinical treatment

All clinical procedures were approved by the Ethical Committee of the First Affiliated Hospital of Sun Yat-sen University. A 21-year-old female patient was referred to the Stomatology Department of the First Affiliated

Table 1 Material properties and number of elements and nodes

Material	Young's modulus/MPa	Poisson's ratio	Number of nodes	Number of elements
Archwire	5.5×10^4	0.289	14,370	2800
Ligature	2.9×10^4	0.30	1872	288
Lock screw	2.0×10^5	0.30	8021	2732
Spherical self-ligating bracket	2.0×10^5	0.30	31,633	20,386
Damon bracket	2.0×10^5	0.30	34,100	20,245
Discovery bracket	2.0×10^5	0.30	29,433	20,126
Adhesive	8.823×10^3	0.25	4115	1965
Tooth	2.0×10^4	0.30	38,002	11,886
Alveolar bone	2.0×10^3	0.30	68,176	21,454
PDL	Nonlinear model		66,911	19,367

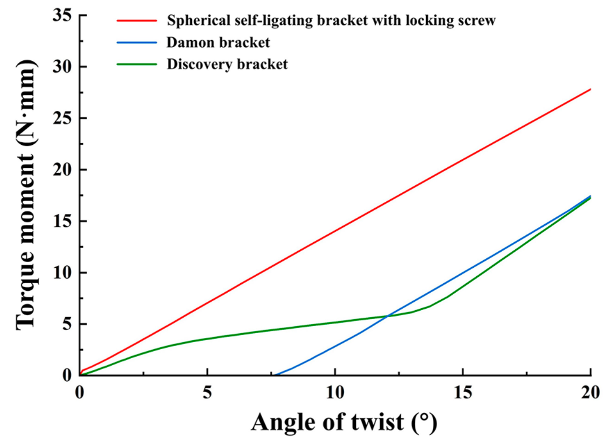

Fig. 4 Torque moment/angle of twist curves of the spherical self-ligating bracket with the lock-hook system, the Damon bracket and the Discovery bracket

Hospital of Sun Yat-sen University. The intraoral examination revealed a Class II division 2 malocclusion characterized by lingually inclined upper incisors and an anterior deep bite. No significant skeletal asymmetry or temporomandibular joint disorders were detected. CBCT indicated that the roots of the anterior teeth, particularly the maxillary central incisors, were in close proximity to the bone cortex (Fig. 3). Spherical self-ligating brackets were employed for treatment.

Results

Evaluation of the torque capabilities of different brackets

A 0.019×0.025-inch SS archwire was utilized to evaluate the torque moment of various brackets at angles of twist ranging from 0° to 20°. As illustrated in Fig. 4, after tightening the lock screw to restrict the archwire, the spherical self-ligating bracket initiated torque expression as the archwire began to rotate. The torque moment increased with the angle of twist, establishing an approximately linear relationship within the 0° to 20° range. In contrast, the Damon bracket began to generate torque only after reaching a twist angle of 7.4°, with the torque moment increasing as the twist angle increased. The torque moment/angle of twist curve of the Discovery bracket exhibited distinct characteristics due to the presence of the ligature. Because of the ligature, the Discovery bracket was able to express torque initially, similar to the spherical self-ligating bracket. However, the torque generated by the Discovery bracket was significantly lower than that produced by the spherical self-ligating bracket. When the initial torque was applied, the ligature experienced elastic deformation, resulting in a linear increase in torque. Upon reaching a twist angle of 2.5°, the ligature began to yield, leading to a nonlinear growth pattern characterized by a progressively decelerating rate of torque moment increase. At a twist angle of 12.7°, the three edges of the archwire made contact with the rigid slots, facilitating a rapid increase in the torque moment. At the same angle of twist, the torque moment of the spherical self-ligating bracket with the lock-hook system was significantly greater than that of both the Damon bracket and the Discovery bracket. The maximum torque moment generated by the spherical self-ligating bracket with the lock-hook system was 27.8 N·mm, which was approximately 1.6 times greater than that of the Damon bracket (17.5 N·mm) and the Discovery bracket (17.3 N·mm).

Fig. 3 Intraoral photographs and CBCT before treatment

Biomechanical effects in the PDL during torque expression

During the expression of torque, different bracket groups exhibited a similar trend in the biomechanical effects on the PDL. As the angle of twist increased, both the von Mises stress and the equivalent strain in the PDL also increased (Figs. 5 and 6). The stress and strain were primarily concentrated in the apical and cervical regions of the tooth. Furthermore, the optimal torque range for the maxillary central incisor was determined by evaluating the PDL stress and strain induced by the spherical self-ligating bracket with the lock-hook system (Fig. 7). At a torque of 10.2 N·mm, the proportion of the PDL good strain area (defined as the area with PDL strain exceeding 0.3% [18]) was 50%. As the torque increased to 17.5 N·mm, the maximum PDL stress reached 0.026 MPa, which is considered the maximum stress that the PDL can withstand [19]. Therefore, when the percentage of the PDL good strain area constituted at least 50% of the total PDL area and the maximum PDL stress did not exceed 0.026 MPa, the torque was determined to range from 10.2 to 17.5 N·mm, which corresponds to a twist angle ranging from 7.2° to 12.7° in the spherical

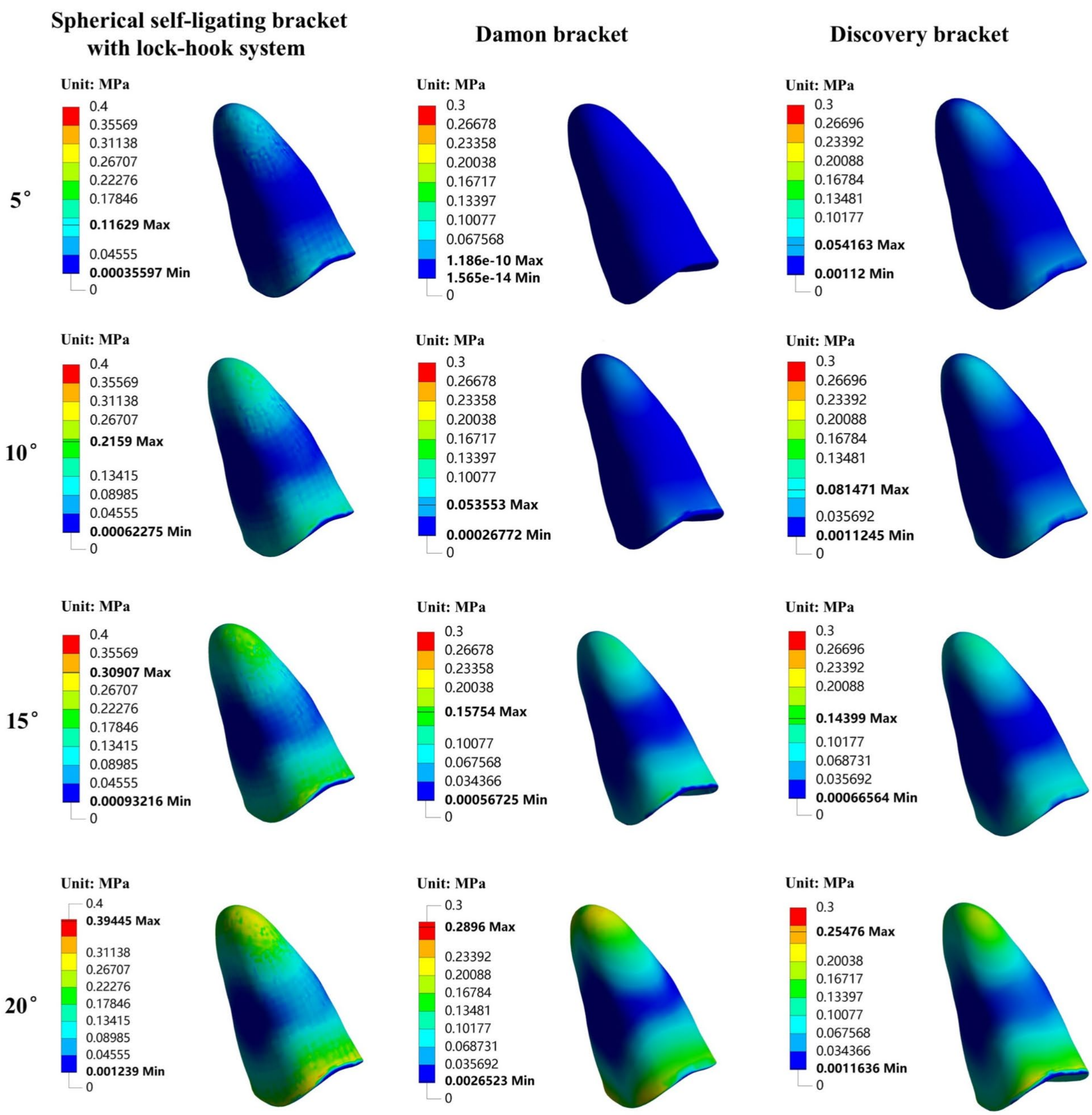

Fig. 5 Equivalent stress of the PDL during torque expression

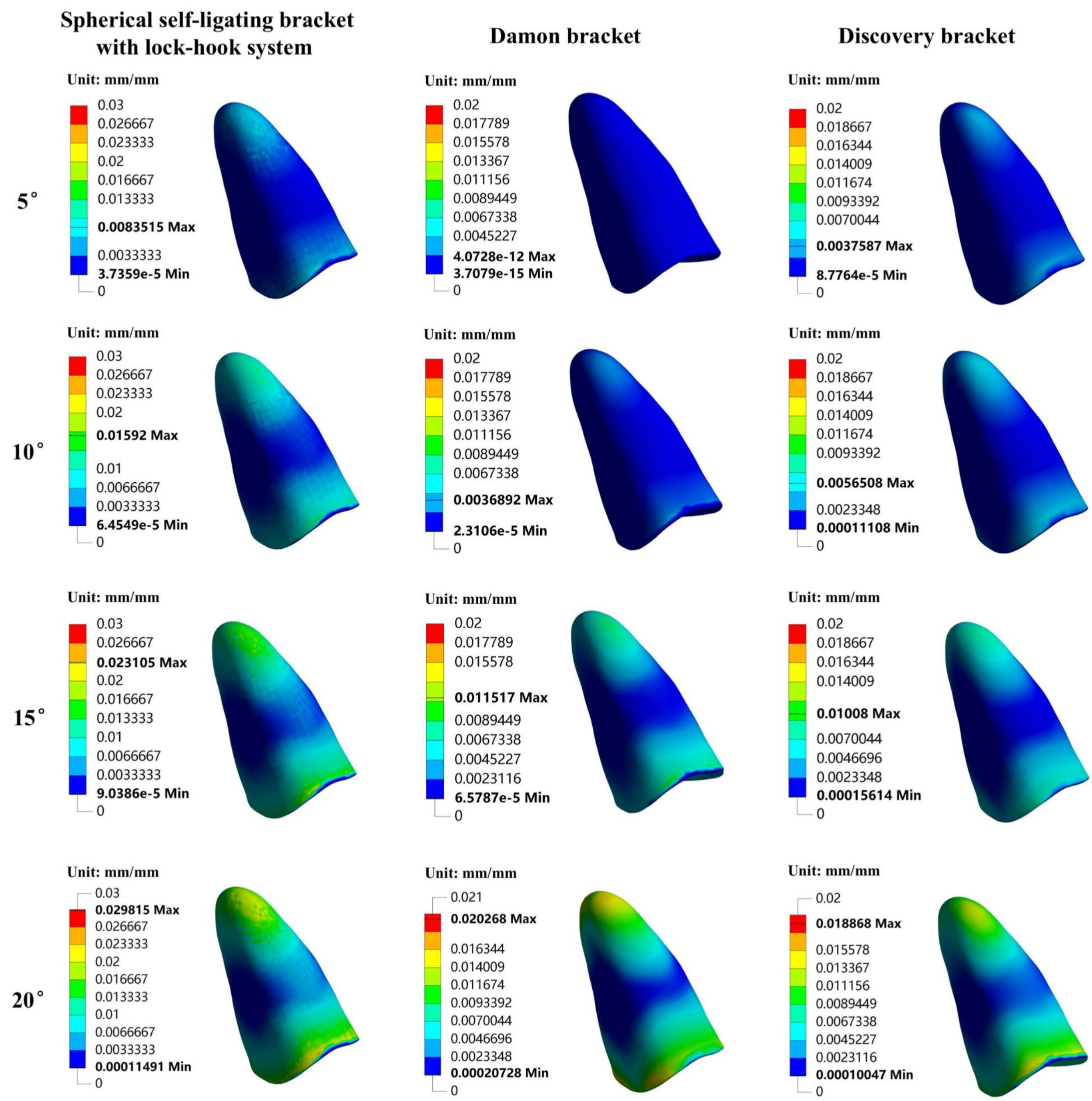

Fig. 6 Equivalent strain of the PDL during torque expression

self-ligating bracket with the lock-hook system. This range is regarded as the appropriate torque value range for the maxillary central incisor.

Clinical findings

After the initial leveling and alignment of the maxillary dentition, a 0.019×0.025-inch SS archwire was incorporated into the spherical self-ligating bracket system to express torque. Two months later, the maxillary incisors, particularly the maxillary right central incisor, continued to exhibit suboptimal labial inclination. CBCT images revealed that the roots were in close proximity to the cortical bone, indicating a high risk of bone fenestration. To address this issue, we tightened the lock screws in the threaded holes of the spherical self-ligating brackets on the maxillary anterior teeth (Fig. 8). Two months later, the retroclined upper incisors had been corrected, and the roots had fully integrated into the maxillary alveolar bone. No significant root resorption was observed throughout the entire treatment period (Fig. 9).

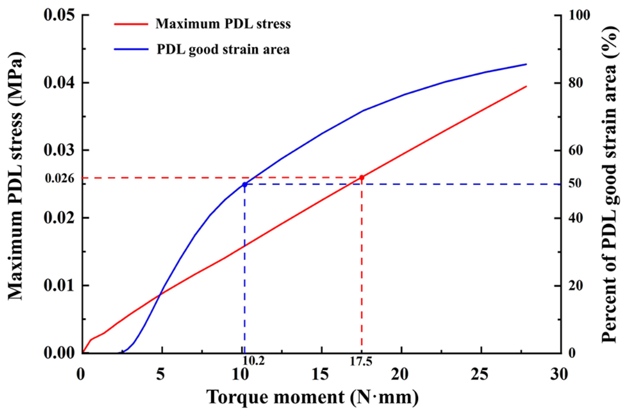

Fig. 7 Appropriate torque range of the maxillary central incisor (taking the spherical self-ligating bracket with the lock-hook system as an example)

Discussion

An appropriate labiolingual inclination of the teeth is crucial for achieving an aesthetically pleasing smile line, an optimal occlusal relationship, and a stable long-term orthodontic outcome. Improper labiolingual inclination can result in deep bite, hinder the retraction of anterior dentition, increase the risk of bone dehiscence and fenestration, and disrupt the establishment of cusp-to-fossa contact between maxillary and mandibular teeth [2]. In fixed orthodontic appliances, the labiolingual inclination of the teeth can be adjusted through the torque generated by the interaction between the brackets and rectangular archwires [20]. Clinicians must be aware of the torque capabilities of the used bracket-archwire systems employed to achieve optimal treatment results. This study is the first to investigate the differences in torque capabilities among the novel spherical self-ligating bracket with a lock-hook system, the Damon bracket, and the Discovery bracket.

Conventional brackets confine archwires within their slots using elastic loops or ligature wires. A significant drawback of elastic ligatures is their rapid loss of force, which can lead to a reduction of up to 50% of the initial force within 24 h. When torque control is essential, SS ligatures are preferred [2, 21]. This study investigated the impact of SS ligatures on torque expression using FEA. The results indicated that the torque expression of the conventional bracket underwent several stages (Fig. 4). The torque of the Discovery bracket varied as its ligature transitioned from elastic to plastic deformation. Due to the limited restraint provided by the ligature, the load transmitted to the bracket was low during the

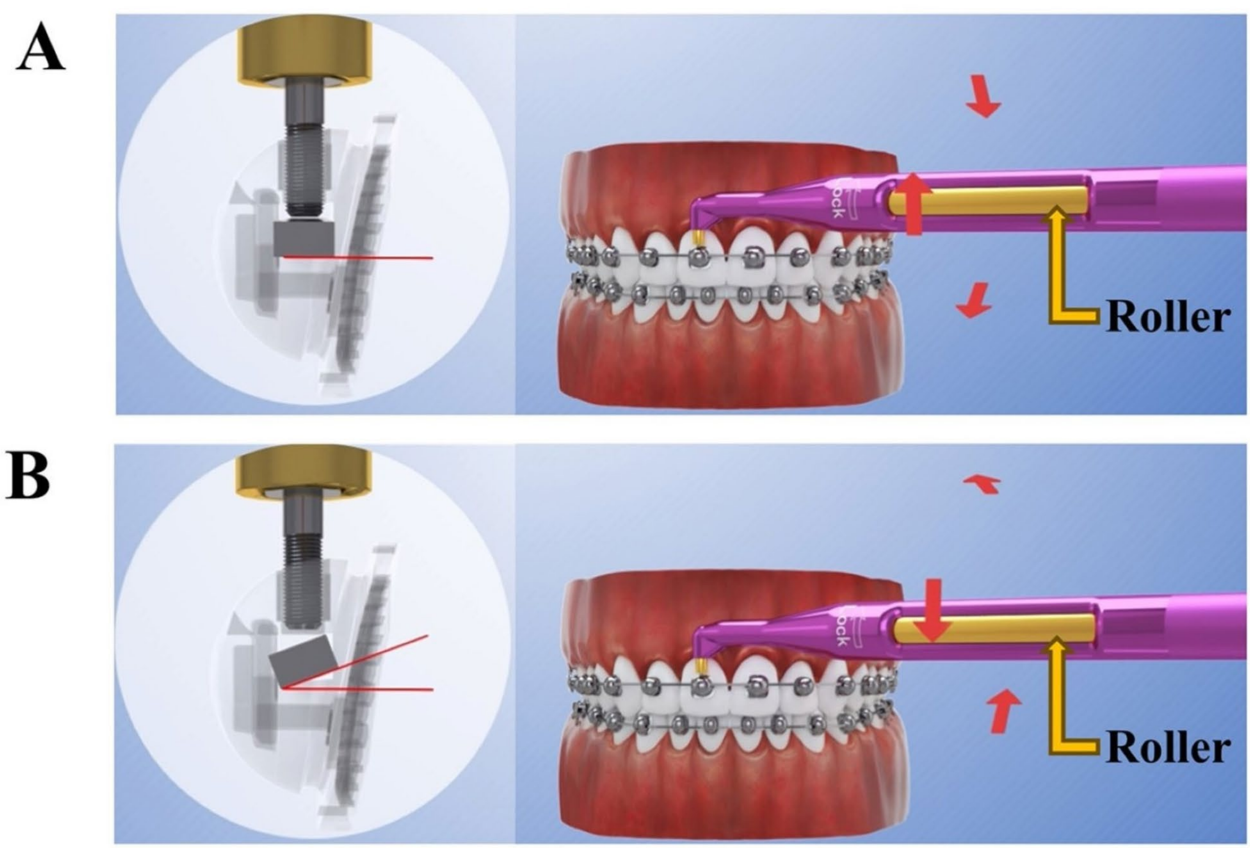

Fig. 8 Instructions for the lock screw of the spherical self-ligating bracket. (**A**) The roller of the wrench rotates in a direction identified by the "Lock" to tighten the screw (clockwise), and (**B**) the roller of the wrench rotates in a opposite direction identified by the "Lock" to loosen the screw (counterclockwise)

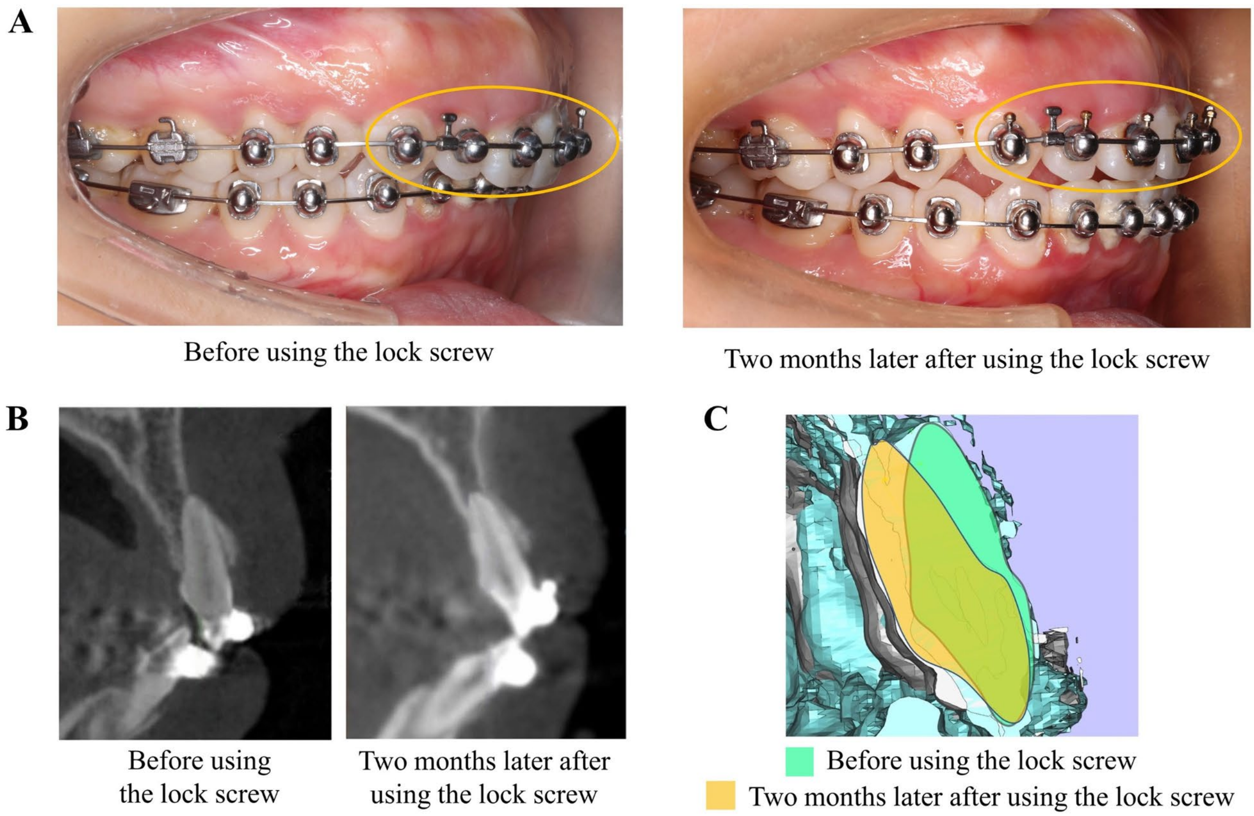

Fig. 9 Torque control after applying the lock screw in the lock-hook system. (**A**) Intraoral photographs, (**B**) CBCT images of the maxillary right central incisor and (**C**) digital overlap of the maxillary right central incisor

initial phase, resulting in a relatively low torque moment. Torque increased rapidly once the three edges of the archwire engaged with the rigid slots. Self-ligating brackets enhance operational efficiency by reducing the frequency of ligature replacements. The sliding doors of passive self-ligating brackets do not exert pressure on the archwires, allowing them to twist freely within the bracket slots until the edges of the archwires make contact with the slot walls. Our study demonstrated that the Damon bracket began to express torque after the archwire rotated beyond 7.4° (Fig. 4). Enhancing bracket prescriptions may be a viable strategy for improving torque control. However, torsional play, particularly in relation to 0.022-inch passive self-ligating brackets, diminishes the differences among various prescriptions, suggesting that the importance of prescription selection may be relatively minor [22, 23]. Active self-ligating brackets typically employ active clips to apply force to the archwires, thereby enhancing torque capability. However, Tomus et al.. reported that more than half of the active clips in Speed brackets were either partially or completely opened during torque expression, leading to significant torque loss [24]. Furthermore, the effectiveness of active self-ligation has been questioned by Brauchli et al., whose study indicated that active clips did not have a clinically significant impact on torque expression [25]. This may be attributed to factors such as temperature sensitivity, irreversible phase transformations, and structural degradation of the flexible spring clips [26]. These discrepancies result in a loss of torque, as the play between the archwire and the slot allows for unwanted twist. In contrast, the spherical self-ligating brackets utilize lock screws that provide stiffness comparable to that of the brackets themselves. The rigid lock screw, through the threaded hole, can engage the archwire against the slot walls to effectively eliminate torsional play, thereby ensuring the better expression of the bracket prescription. Our study revealed that the spherical self-ligating bracket with the lock-hook system transmitted torque dynamically as the archwire began to rotate, generating the highest torque moment at the same angle of twist (Fig. 4). This suggests that the spherical self-ligating bracket with the lock-hook system can significantly enhance torque expression.

The sliding technique is one of the most commonly employed methods for orthodontic space closure, and the 0.022-inch bracket system has been favored by numerous orthodontists due to its advantages in sliding mechanics [27]. However, the 0.022-inch bracket system demonstrates deficiencies in torque performance [28]. To address this limitation, practitioners often resort to time-consuming wire bends, auxiliary devices, or special ligations [4]. In contrast, the spherical self-ligating bracket achieves torque control through the straightforward rotation of a wrench to tighten the screw (Fig. 8), a method that has been successfully implemented in clinical practice. As illustrated in Fig. 9, the spherical self-ligating bracket with the lock-hook system can attain optimal torque control. It is worth noting that this approach has the potential to expand the variety of archwire types utilized during torque expression, thereby facilitating the use of smaller SS archwires or even nickel-titanium archwires in the early stages of tooth levelling to control torque.

The PDL can initiate biochemical and cellular activities essential for bone remodeling [7] and facilitate orthodontic tooth movement [8]. Assessing changes in stress and strain within the PDL is crucial for understanding the biological behaviors of the dentoalveolar complex. However, no specialized device has yet been developed to directly measure the magnitude of stress and strain in the PDL. FEA can evaluate mechanical changes in biological systems, enabling the quantification of periodontal stress and strain. The accuracy of the FEA results is significantly influenced by the material properties of the models [29]. Therefore, it is essential to investigate the properties of the PDL to obtain more realistic stress-strain data under orthodontic forces.

The constitutive models of PDL in FEA are generally categorized into four types: linear elastic, hyperelastic, viscoelastic, and fiber matrix models [30]. Most finite element studies have treated the PDL as an isotropic linear elastic material due to the simplicity of this approach. However, studies have shown that the PDL exhibits nonlinear properties, and its stress-strain relationship can be described by an exponential function curve [31, 32]. The viscoelastic model captures the time-dependent mechanical behavior of the PDL, although it exhibits hysteresis in its stress-strain response [33]. Given that collagen fibers constitute 50–75% of the PDL's volume, some studies have proposed using a fiber matrix model to represent the behavior of the PDL [34, 35]. However, this approach is complex and time-consuming, and variations in fiber alignment angle and fiber stiffness do not significantly affect the stress distribution [36]. Consequently, many studies have opted to exclude collagen fibers and have treated the PDL as a homogeneous material [9]. Natali et al.. utilized human incisors to investigate the relationship between orthodontic force and the mechanical response of the PDL, finding that the Ogden hyperelastic model provided a better fit for in vivo experimental data [13]. To accurately represent the hyperelastic behavior of the PDL during initial loading [37], this study ultimately employed the nonlinear third-order Ogden hyperelastic model.

Orthodontic treatment should be conducted within a safe physiological range. Previous studies have primarily focused on mechanical experiments or simplistic models of brackets and archwires [15, 24, 38]. This study investigated the biomechanical changes in the PDL during torque expression. Our findings demonstrated that an increase in the angle of twist resulted in a corresponding rise in the generated torque moment for each bracket system, which was accompanied by an escalation in the stress and strain experienced by the PDL (Figs. 5 and 6). Clinically relevant torque moments are suggested to range from 5 to 20 N·mm, however, the literature lacks conclusive evidence regarding the optimal torque moment [39]. Exploring the appropriate torque range can minimize clinical side effects caused by excessive orthodontic forces, ensure the health of teeth and periodontal tissues, and facilitate efficient tooth movement with a reduced treatment duration. The PDL plays a crucial role in the physiological process of tooth movement. Qian et al.. noted that the tooth remained stationary until the PDL strain reached 0.03%, at which point bone reconstruction associated with tooth movement was initiated. Subsequently, a positive linear correlation was established between the rate of tooth movement and the PDL strain. When the PDL strain was increased to 0.3%, the rate of tooth movement rate reached its peak [18]. Lee et al.. reported that the PDL can withstand a maximum stress of 0.026 MPa [19]. If the stress exceeded the threshold, it may lead to periodontal ischemia and root resorption. Based on the aforementioned studies, the maximum PDL stress should remain below 0.026 MPa to mitigate the risk of root resorption and tissue necrosis. Furthermore, area where the PDL strain exceeds 0.3% can be identified as good strain area. The tooth will fulfill high mobility efficiency when the PDL good strain area constitutes more than 50% of the total PDL area. The appropriate applied torque should maintain the PDL stress within safe limits and maximize the proportion of good strain areas in the PDL. Using the spherical self-ligating bracket with the lock-hook system as an example, this study revealed that the optimal torque for the maxillary incisor ranged from 10.2 to 17.5 N·mm. Within this range, the PDL stress was confined to a maximum of 0.026 MPa, and the percentage of PDL good strain areas exceeded 50%, resulting in the most efficient tooth movement with minimal risk of tissue damage.

The present study demonstrated strengths in optimizing material properties in the FEA. We conducted tensile test to determine the mechanical properties of the archwire and ligature, employing the third-order Ogden model to characterize the PDL. However, due to the discrepancies between the experimental configuration and the clinical setting, our findings may not fully reflect actual clinical scenarios. Complex variables in orthodontic treatment, such as saliva, PDL health, individual responses to applied torque, and variability in malocclusion, can influence clinical outcomes [40]. Neverthelss, we provided a qualitative trend in torque expression among different brackets and biomechanical changes in the PDL. Considering that SS archwires are typically placed in brackets after nickel-titanium wires have leveled the brackets, our study did not include adjacent teeth in the model and assumed that the brackets on both the modeled tooth and adjacent teeth were at the same level. Additionally, torque may be influenced by various factors, including tooth anatomy, bracket positioning, and archwire dimensions [16]. Of note, recent findings have highlighted the importance of the bracket slot and tie wing deformation during torque expression [41–43]. In future research, we will consider interproximal contact between adjacent teeth, further analyze impact factors like archwire-induced deformation in bracket system, and compare torque expression across various orthodontic appliances and their components, assisting orthodontists in the selection of appropriate brackets for clinical use.

Conclusion

1. Compared to the passive self-ligating bracket (Damon) and conventional bracket (Discovery), the spherical self-ligating bracket featuring a lock-hook system can significantly enhance torque expression, resulting in a greater torque moment.
2. Clinicians should apply torque within a safe physiological range, as the stress and strain in the PDL increase during torque expression. Considering the stress and strain in the PDL, the appropriate torque range for maxillary central incisors is 10.2 to 17.5 N·mm, which corresponds to a twist angle ranging from 7.2° to 12.7° in the spherical self-ligating bracket with the lock-hook system.

Abbreviations

SS	Stainless steel
PDL	Periodontal ligament
FEA	Finite element analysis
CBCT	Cone beam computed tomography

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Not applicable.

Author contributions
Yudong Liu and Longmei Guo contributed equally to this work.Bing Guo, Taicong Chen, and Li Ji were corresponding authors.Y.D.L and L.M.G conducted analysis and wrote the manuscript. Y.Q.F collected clinical data. J.H.H and Q.Y.D performed software manipulation. Z.Y.C and W.L.S revised the manuscript. L.J, T.C.C and B.G contributed to the conception of the study and final approval of the manuscript. All authors gave final approval of the version of the manuscript to be published.

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Data availability
The data generated or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This study was conducted in accordance with the Declaration of Helsinki. The present study was approved by Ethics Committee of the First Affiliated Hospital of Sun Yat-sen University ([2023]800). Informed consent was obtained from all of the participants in this study for clinical information and images.

Consent for publication
Available (if requested).

Clinical trial number
Not applicable.

Competing interests
The authors declare no competing interests.

Author details
[1]Department of Stomatology, The First Affiliated Hospital, Sun Yat-Sen University, Guangzhou 510080, China
[2]School of Civil Engineering and Transportation, South China University of Technology, Guangzhou 510640, China
[3]Guangdong Artificial Intelligence and Digital Economy Laboratory, Guangzhou 510335, China
[4]Guangzhou OO Stomatology Institute, Guangzhou 510080, China

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