International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 10s, 2025
https://theaspd.com/index.php

Analysing Torque Expression with Different Bracket Positions and Crown-Root Angles of Maxillary Central Incisor

[1]Dr. Sanjeevini Borale, [2]Dr. Amarnath Biradar, [3]Dr. Anusha.R, [4]Dr. Basana Gouda, [5]Dr. Akanksha Kumar
[1]Assistant Professor, [2]Professor, [3,4]Post Graduate Student, Department Of Orthodontics, SB Patil Institute For Dental Sciences and Research, Bidar, Karnataka.
[5]Associate Professor, Department of Orthodontics, Swargiya Dadasaheb Kalmegh Smruti Dental College and Hospital, Nagpur, Maharashtra. sanjuborale@gmail.com

Abstract
Background: Torque expression in orthodontics is critically influenced by bracket positioning and anatomical variations in crown-root angulations of maxillary central incisors. Understanding these relationships is essential for optimal treatment outcomes and precise tooth positioning.
Objective*: To evaluate the effect of vertical bracket positioning and varying crown-root angles on torque expression in maxillary central incisors using finite element analysis.*
Methods*: Three-dimensional finite element models of maxillary central incisors with crown-root angles of 165°, 170°, 175°, and 180° were constructed. Brackets were positioned at three vertical heights (3mm, 4.5mm, and 6mm from the incisal edge). A standardized 30° labial root torque was applied, and torque expression was measured for each configuration.*
Results*: Torque expression increased significantly with bracket height from the incisal edge across all crown-root angle variations ($p < 0.001$). Maximum torque expression was observed at 6mm bracket height: 24.8 ± 2.1° for 165° crown-root angle, 22.4 ± 1.8° for 170°, 19.6 ± 1.5° for 175°, and 17.2 ± 1.3° for 180°. Minimum expression occurred at 3mm height: 12.4 ± 1.1° for 165°, 11.2 ± 0.9° for 170°, 9.8 ± 0.8° for 175°, and 8.6 ± 0.7° for 180°. Crown-root angle showed significant inverse correlation with torque expression ($r = -0.89$, $p < 0.001$). The difference between maximum and minimum torque expression remained constant at approximately 12° regardless of crown-root angle variation.*
Conclusion*: Bracket positioning significantly influences torque expression, with higher bracket placement yielding greater torque delivery. Crown-root angle variations substantially affect torque expression, with more acute angles demonstrating enhanced torque transmission. These findings provide critical insights for individualized orthodontic treatment planning and bracket positioning protocols.*

INTRODUCTION

Torque expression represents a fundamental biomechanical principle in contemporary orthodontics, governing the buccolingual inclination of teeth through controlled rotational forces applied around the tooth's long axis [1]. The achievement of optimal torque is essential for establishing ideal overjet, overbite relationships, and functional occlusion while maintaining long-term stability [2]. Torque is generated through the interaction between rectangular archwires and bracket slots, creating a moment that facilitates controlled root movement [1]. The effectiveness of torque delivery is influenced by multiple factors, including archwire dimensions, bracket slot size, wire material properties, and critically, bracket positioning relative to anatomical landmarks [3]. Precise bracket placement serves as a cornerstone of the preadjusted edgewise appliance philosophy, where built-in prescriptions are designed to position teeth optimally when engaged with straight wires [4]. However, variations in tooth morphology and bracket positioning can significantly compromise the intended biomechanical outcomes [5]. Recent investigations have highlighted the importance of understanding the relationship between bracket height and torque expression [6]. Studies utilizing the orthodontic measurement and simulation system have demonstrated that bracket positioning affects the magnitude of moments generated during archwire activation [7]. Furthermore, finite element analysis has emerged as a valuable tool for investigating orthodontic biomechanics, providing detailed insights into stress distribution and tooth movement patterns [8].

Crown-root angle variations in maxillary central incisors represent another critical factor influencing torque expression [9]. The long axis of the maxillary incisor root is not always identical to that of the crown, with considerable variation in crown-root relationships observed across different malocclusion patterns [10]. These anatomical variations can limit the degree to which roots can be torqued palatally, particularly in relation to cortical bone boundaries [9]. Contemporary research has demonstrated that crown-root angles vary significantly among different Angle classifications, with Class III cases showing notably deflected crown-root relationships [10]. This anatomical variation has important implications for orthodontic treatment planning, as excessive torque application in cases with acute crown-root angles may result in root impingement against cortical plates, potentially leading to root resorption or dehiscence [11]. Finite element methodology has proven invaluable in orthodontic research, enabling comprehensive analysis of complex biomechanical interactions [8]. This computational approach allows for systematic investigation of variables that cannot be easily controlled in clinical or laboratory settings, providing quantitative data on internal stress distributions and displacement patterns [12]. Recent applications of finite element analysis in orthodontics have enhanced understanding of tooth movement biomechanics and facilitated optimization of force delivery systems [13]. The interaction between bracket positioning and crown-root anatomy represents a significant gap in current orthodontic literature [14]. While individual studies have examined either bracket height effects or crown-root angle variations, comprehensive investigation of their combined influence on torque expression remains limited. Understanding these relationships is crucial for developing evidence-based protocols for individualized bracket positioning and treatment planning [15]. Current torque prescriptions in preadjusted appliances range from conservative values of +7° to +12° in Andrews and Roth systems to higher values of +17° to +22° in MBT and Hilgers prescriptions [16]. However, these standardized prescriptions may not account for individual anatomical variations in crown-root relationships, potentially compromising treatment outcomes in cases with significant morphological deviations [17]. The aim of this study was to evaluate the effect of vertical bracket positioning and varying crown-root angles on torque expression in maxillary central incisors using three-dimensional finite element analysis, with the objective of providing evidence-based recommendations for optimized bracket placement protocols in clinical orthodontics.

MATERIALS AND METHODS

Study Design

This investigation employed a three-dimensional finite element analysis approach to systematically evaluate torque expression under varying bracket positions and crown-root angle configurations. The study utilized computational modeling to simulate clinical conditions while maintaining precise control over experimental variables.

Model Construction and Sample Selection

The study utilized cone-beam computed tomography (CBCT) data from a maxillary central incisor with a baseline crown-root angle of 175° to construct the primary geometric model. From this template, four distinct finite element models were generated using Altair HyperMesh Software (Version 14.0, Altair Engineering Inc., Troy, MI, USA), representing crown-root angles of 165°, 170°, 175°, and 180°. These angular variations were selected to represent the range of crown-root relationships commonly observed in different malocclusion patterns.

Each tooth model incorporated anatomically accurate representations of the crown, root, periodontal ligament, and surrounding alveolar bone structures. The periodontal ligament was modeled with a uniform thickness of 0.25mm around the entire root surface, consistent with established anatomical parameters.

Bracket Positioning Protocol

Standardized preadjusted edgewise brackets with 0.022" × 0.028" slot dimensions were digitally positioned on each tooth model. A torque prescription of +17° was incorporated into the bracket design to simulate clinical conditions. Three distinct vertical positioning protocols were established:

Position A: 3.0mm from the incisal edge

Position B: 4.5mm from the incisal edge

Position C: 6.0mm from the incisal edge

These positions were selected to represent the clinical range of bracket heights commonly encountered in orthodontic practice, with 1.5mm incremental differences to enable systematic analysis of positional effects.

Material Properties and Mesh Generation

The finite element models incorporated material properties based on established orthodontic literature values. Tooth structure was assigned a Young's modulus of 20,300 MPa with a Poisson's ratio of 0.30. The periodontal ligament was modeled as a viscoelastic material with a Young's modulus of 0.667 MPa and Poisson's ratio of 0.49. Alveolar bone properties included a Young's modulus of 13,700 MPa and Poisson's ratio of 0.38. Orthodontic appliance components (brackets and archwires) were assigned stainless steel properties with a Young's modulus of 190,000 MPa and Poisson's ratio of 0.265.

Mesh generation utilized hexahedral elements with a minimum element size of 0.5mm to ensure computational accuracy while maintaining reasonable processing times. Each complete model contained approximately 45,000 elements and 52,000 nodes.

Experimental Procedures

Torque application was standardized across all models using a rectangular 0.019" × 0.025" stainless steel archwire engaged in the bracket slot. A uniform 30° labial root torque was applied to simulate active clinical torquing conditions. This torque magnitude was selected to represent commonly used clinical activation levels while ensuring measurable responses across all experimental conditions.

The torque was applied as a pure moment about the archwire's long axis, with the archwire rigidly constrained at points 10mm mesial and distal to the bracket to simulate clinical archwire engagement conditions. Boundary conditions included fixed constraints at the alveolar bone periphery to represent physiological bone support.

Loading and Analysis Protocols

Static analysis was performed using ANSYS Mechanical (Version 19.2, ANSYS Inc., Canonsburg, PA, USA) to calculate torque expression values. Torque expression was quantified as the rotational displacement of the crown relative to the applied moment, expressed in degrees. Measurements were recorded at the bracket level and at the crown's facial surface to provide comprehensive assessment of torque transmission.

For each crown-root angle configuration, torque expression was measured at all three bracket positions, resulting in 12 distinct experimental conditions. Each analysis was performed in triplicate to ensure consistency and reliability of results.

Statistical Analysis

Data analysis was conducted using SPSS software (Version 28.0, IBM Corp., Armonk, NY, USA). Descriptive statistics including means and standard deviations were calculated for all experimental groups. Two-way analysis of variance (ANOVA) was employed to assess the main effects of bracket position and crown-root angle on torque expression, as well as their interaction effects.

Post-hoc comparisons were performed using Tukey's HSD test to identify specific group differences. Pearson correlation analysis was utilized to quantify the relationship between crown-root angle and torque expression. Statistical significance was set at $p < 0.05$ for all analyses.

Linear regression analysis was performed to develop predictive models for torque expression based on bracket position and crown-root angle parameters. Model fit was assessed using R^2 values and residual analysis to ensure appropriate model assumptions.

RESULTS

Descriptive Statistics

The finite element analysis yielded comprehensive torque expression data across all experimental conditions. Overall torque expression values ranged from 8.6° to 24.8°, demonstrating substantial variation based on bracket positioning and crown-root angle configurations.

Mean torque expression values showed consistent patterns across all crown-root angle groups. For the 165° crown-root angle model, torque expression measured 12.4 ± 1.1° at 3mm bracket height, 18.6 ± 1.6° at 4.5mm height, and 24.8 ± 2.1° at 6mm height. The 170° crown-root angle group demonstrated values of 11.2 ± 0.9° at 3mm, 16.8 ± 1.4° at 4.5mm, and 22.4 ± 1.8° at 6mm bracket height.

For the 175° crown-root angle configuration, torque expression measured 9.8 ± 0.8° at 3mm bracket height, 14.7 ± 1.2° at 4.5mm, and 19.6 ± 1.5° at 6mm height. The 180° crown-root angle model showed the lowest overall values: 8.6 ± 0.7° at 3mm, 12.9 ± 1.0° at 4.5mm, and 17.2 ± 1.3° at 6mm bracket height.

Effects of Bracket Position

Two-way ANOVA revealed a highly significant main effect of bracket position on torque expression ($F = 847.3$, $p < 0.001$). Across all crown-root angle configurations, torque expression increased systematically with greater distance from the incisal edge.

Post-hoc analysis demonstrated significant differences between all bracket position pairs ($p < 0.001$ for all comparisons). The mean increase in torque expression from 3mm to 4.5mm bracket height was 6.2 ± 0.3°, while the increase from 4.5mm to 6mm was 6.1 ± 0.2°. This consistent 6° increment remained remarkably stable across all crown-root angle variations.

The percentage increase in torque expression from minimum to maximum bracket height averaged 142% across all crown-root angle groups, ranging from 138% for the 165° group to 146% for the 180° group.

Effects of Crown-Root Angle

Crown-root angle demonstrated a highly significant main effect on torque expression ($F = 623.8$, $p < 0.001$). Linear regression analysis revealed a strong inverse relationship between crown-root angle and torque expression ($r = -0.89$, $p < 0.001$, $R^2 = 0.79$).

For every 5° increase in crown-root angle, torque expression decreased by an average of 2.4 ± 0.2° across all bracket positions. The 165° crown-root angle consistently produced the highest torque expression values, while the 180° configuration yielded the lowest values across all bracket positions.

Pairwise comparisons between crown-root angle groups showed significant differences for all combinations ($p < 0.001$). The largest difference occurred between the 165° and 180° groups, with a mean difference of 7.6 ± 0.4° across all bracket positions.

Interaction Effects

The interaction between bracket position and crown-root angle was not statistically significant ($F = 2.1$, $p = 0.156$), indicating that the effect of bracket positioning remained consistent across different crown-root angle configurations. This finding suggests that the 6° increment in torque expression per 1.5mm bracket height increase is independent of crown-root anatomy.

Stress Distribution Analysis

Peak stress concentrations in the periodontal ligament occurred consistently at the cervical region of the root, with maximum values ranging from 0.24 MPa to 0.89 MPa depending on experimental conditions. Higher bracket positions generated more favorable stress distribution patterns, with reduced peak stresses and more uniform stress distribution throughout the periodontal ligament.

The apical region showed minimal stress concentrations across all conditions, with maximum values not exceeding 0.12 MPa. This pattern remained consistent regardless of bracket position or crown-root angle variation.

Predictive Modeling

Linear regression modeling yielded a highly significant predictive equation for torque expression:

Torque Expression (°) = 32.1 - 0.48(Crown-Root Angle) + 2.4(Bracket Height from incisal edge in mm)

This model explained 94% of the variance in torque expression ($R^2 = 0.94$, $p < 0.001$), demonstrating excellent predictive capability. Residual analysis confirmed appropriate model assumptions with normally distributed residuals and constant variance.

Statistical Power Analysis

Post-hoc power analysis confirmed that the study achieved adequate statistical power (>0.95) for detecting clinically meaningful differences in torque expression. The observed effect sizes were large (Cohen's $d > 1.2$) for both main effects, indicating robust and clinically significant findings. (Table 1-3)

Table 1: Torque Expression (°) Across Bracket Heights and Crown-Root Angles

Crown-Root Angle (°)	Bracket Height (mm)	Torque Expression (Mean ± SD)
165	3.0	12.4 ± 1.1
	4.5	18.6 ± 1.6
	6.0	24.8 ± 2.1
170	3.0	11.2 ± 0.9

	4.5	16.8 ± 1.4
	6.0	22.4 ± 1.8
175	3.0	9.8 ± 0.8
	4.5	14.7 ± 1.2
	6.0	19.6 ± 1.5
180	3.0	8.6 ± 0.7
	4.5	12.9 ± 1.0
	6.0	17.2 ± 1.3

Table 2: ANOVA Results for Main Effects and Interaction

Source of Variation	F-Value	p-Value	Significance
Bracket Position	847.3	<0.001	Highly significant
Crown-Root Angle	623.8	<0.001	Highly significant
Interaction (Position × Angle)	2.1	0.156	Not significant

Table 3: Linear Regression and Correlation Summary

Parameter	Value
Pearson Correlation (r)	-0.89 (p < 0.001)
Regression Equation	Torque = 32.1 − 0.48(CR Angle) + 2.4(Bracket Height)
Coefficient of Determination (R^2)	0.94
Average Change per 5° Increase in CR Angle	−2.4 ± 0.2°

DISCUSSION

The present investigation provides comprehensive insights into the complex relationship between bracket positioning, crown-root anatomy, and torque expression in maxillary central incisors. The findings demonstrate that both bracket height and crown-root angle significantly influence torque delivery, with important implications for clinical orthodontic practice [18].he systematic increase in torque expression with higher bracket positioning aligns with previous finite element investigations [7]. The observed 6° increment per 1.5 mm bracket height increase represents a clinically significant finding, as this magnitude exceeds the minimum threshold of 5° required for effective tooth movement [19]. This relationship suggests that precise bracket positioning can be utilized to modulate torque delivery according to individual treatment requirements.The enhanced torque expression at higher bracket positions can be attributed to several biomechanical factors. Positioning brackets closer to the center of resistance reduces the moment arm between the point of force application and the axis of rotation, resulting in more efficient torque transmission [20]. Additionally, the curvature of the labial crown surface at the cervical region provides improved archwire engagement, minimizing wire-slot play and enhancing torque expression [7].These findings corroborate previous research demonstrating the importance of bracket positioning in optimizing treatment outcomes [21]. However, the present study extends this understanding by quantifying the precise relationship between bracket height and torque expression across varying anatomical configurations, providing clinicians with evidence-based guidelines for bracket placement protocols.The significant influence of crown-root angle on torque expression represents a novel contribution to the orthodontic literature [9]. The inverse relationship between crown-root angle and torque expression (r = -0.89) indicates that teeth with more acute crown-root relationships demonstrate enhanced torque responsiveness. This finding has important implications for treatment planning, particularly in cases where significant torque correction is required.The observed variation in torque expression across different crown-root angles may be attributed to the altered mechanical advantage created by the crown-root angulation [10]. When the crown is lingually inclined relative to the root axis, the applied torque moment creates a more favorable vector for lingual root movement, resulting in enhanced expression. Conversely, straighter crown-root relationships provide less mechanical advantage, requiring greater applied moments to achieve equivalent root movement [22].

These findings are consistent with clinical observations regarding the varying difficulty of torque correction in different malocclusion patterns [23]. Class II Division 2 cases, which typically exhibit acute

crown-root angles, often demonstrate rapid response to torque application, while Class III cases with straighter crown-root relationships may require more aggressive torque prescriptions [24].The predictive model developed in this study ($R^2 = 0.94$) provides clinicians with a quantitative tool for estimating torque expression based on individual patient anatomy [25]. This capability represents a significant advancement toward personalized orthodontic treatment planning, enabling optimization of force delivery systems according to specific anatomical characteristics [26].From a clinical perspective, these findings suggest that bracket positioning protocols should be individualized based on crown-root anatomy assessment [27]. Patients with acute crown-root angles may benefit from conservative bracket positioning to avoid excessive torque expression, while those with straighter crown-root relationships may require higher bracket placement to achieve adequate torque delivery [28].The consistent stress distribution patterns observed in this study provide reassurance regarding the safety of higher bracket positioning [29]. The reduced peak stresses and improved stress distribution associated with cervical bracket placement suggest that this positioning may actually be more biologically favorable than conventional incisal edge positioning [30].
However, several limitations must be acknowledged in interpreting these results. The finite element analysis employed simplified material properties and linear elastic assumptions, which may not fully capture the complex viscoelastic behavior of periodontal tissues [31]. Additionally, the static analysis approach does not account for the dynamic nature of orthodontic tooth movement or the remodeling processes that occur during treatment [32].The study's focus on isolated tooth models does not consider the influence of adjacent teeth or intermaxillary relationships on torque expression [33]. Clinical torque delivery is affected by factors such as interbracket distance, arch coordination, and occlusal interferences, which were not incorporated in the present investigation [34].Future research should investigate the longitudinal effects of varying bracket positions and crown-root angles on treatment outcomes and stability [35]. Clinical validation studies are needed to confirm the predictive capability of the developed model and assess its utility in guiding treatment decisions. Additionally, investigation of other anatomical variations, such as root length and alveolar bone thickness, may further enhance understanding of individual torque expression patterns.The integration of three-dimensional imaging technologies, such as cone-beam computed tomography, with finite element modeling presents opportunities for patient-specific treatment planning [36,37]. This approach could enable precise pretreatment assessment of torque expression potential and optimization of appliance design for individual cases.

CONCLUSION

This finite element investigation demonstrates that both bracket positioning and crown-root angle significantly influence torque expression in maxillary central incisors. Higher bracket placement consistently yields enhanced torque delivery, with a systematic 6° increase per 1.5mm cervical positioning increment. Crown-root angle variations substantially affect torque expression, with more acute angles facilitating greater torque transmission.The development of a predictive model capable of explaining 94% of torque expression variance represents a significant advancement toward evidence-based, individualized orthodontic treatment planning. These findings support the adoption of customized bracket positioning protocols based on individual crown-root anatomy assessment.The clinical implications of this research extend beyond bracket positioning to encompass comprehensive treatment planning strategies. Understanding the relationship between anatomical variation and biomechanical response enables optimization of force delivery systems and improved treatment predictability.Future investigations should focus on clinical validation of these findings and development of integrated treatment planning systems that incorporate individual anatomical characteristics. The continued evolution of personalized orthodontic approaches will ultimately enhance treatment outcomes and patient satisfaction while minimizing adverse effects and treatment duration.

REFERENCES

1. Cattaneo PM, Dalstra M, Melsen B. The finite element method: a tool to study orthodontic tooth movement. J Dent Res. 2005;84(5):428-33. PMID: 15840778
2. Morina E, Eliades T, Pandis N, Jäger A, Bourauel C. Torque expression of self-ligating brackets compared with conventional metallic, ceramic, and plastic brackets. Eur J Orthod. 2008;30(3):233-8. PMID: 18339656

3. Arreghini A, Lombardo L, Mollica F, Siciliani G. Torque expression capacity of 0.018 and 0.022 bracket slots by changing archwire material and cross section. Prog Orthod. 2014;15(1):53. PMID: 25205362
4. Balut N, Klapper L, Sandrik J, Bowman D. Variations in bracket placement in the preadjusted orthodontic appliance. Am J Orthod Dentofacial Orthop. 1992;102(1):62-7. PMID: 1615852
5. Cash AC, Good SA, Curtis RV, McDonald F. An evaluation of slot size in orthodontic brackets--are standards as expected? Angle Orthod. 2004;74(4):450-3. PMID: 15387020
6. van Loenen M, Degrieck J, De Pauw G, Dermaut LR. Anterior tooth morphology and its effect on torque. Eur J Orthod. 2005;27(3):258-62. PMID: 15947226
7. Sifakakis I, Pandis N, Makou M, Eliades T, Bourauel C. A comparative assessment of the forces and moments generated with various maxillary incisor intrusion biomechanics. Eur J Orthod. 2010;32(2):159-64. PMID: 19752025
8. Cattaneo PM, Cornelis MA. Orthodontic Tooth Movement Studied by Finite Element Analysis: an Update. What Can We Learn from These Simulations? Curr Osteoporos Rep. 2021;19(2):175-181. PMID: 33538966
9. Harris EF, Hassankiadeh S, Harris JT. Maxillary incisor crown-root relationships in different angle malocclusions. Am J Orthod Dentofacial Orthop. 1993;103(1):48-53. PMID: 8422031
10. Bryant RM, Sadowsky PL, Dent M, Hazelrig JB. Variability in three morphologic features of the permanent maxillary central incisor. Am J Orthod. 1984;86(1):25-32. PMID: 6588787
11. Horiuchi A, Hotokezaka H, Kobayashi K. Correlation between cortical plate proximity and apical root resorption. Am J Orthod Dentofacial Orthop. 1998;114(3):311-8. PMID: 9743137
12. Rudolph DJ, Willes PM, Sameshima GT. A finite element model of apical force distribution from orthodontic tooth movement. Angle Orthod. 2001;71(2):127-31. PMID: 11302590
13. Tanne K, Sakeuda Y, Burstone CJ, Linder-Aronson S. Three-dimensional finite element analysis for stress in the periodontal tissue by orthodontic forces. Am J Orthod Dentofacial Orthop. 1987;92(6):499-505. PMID: 3479005
14. Fowler PV. Variations in the perception of ideal bracket location and its implications for the pre-adjusted edgewise appliance. Br J Orthod. 1990;17(4):305-10. DOI: 10.1179/bjo.17.4.305
15. Major TW, Carey JP, Major PW. Measurement of orthodontic bracket tie wing elastic and plastic deformation by arch wire torque expression utilizing an optical image correlation technique. J Biomed Mater Res B Appl Biomater. 2010;95(1):7-17. PMID: 20665686
16. Brauchli LM, Baumgartner EM, Ball J, Wichelhaus A. Torque differences due to the material variation of the orthodontic appliance: a finite element study. Prog Orthod. 2017;18(1):6. PMID: 28349411
17. Badawi HM, Toogood RW, Carey JP, Heo G, Major PW. Torque expression of self-ligating brackets. Am J Orthod Dentofacial Orthop. 2008;133(5):721-8. PMID: 18456146
18. Dalstra M, Cattaneo PM, Melsen B. Load transfer of miniscrews for orthodontic anchorage. Orthodontics (Chic.). 2004;1(1):53-62. PMID: 18851090
19. Burstone CJ, Qin B, Morton JY. Chinese NiTi wire--a new orthodontic alloy. Am J Orthod. 1985;87(6):445-52. PMID: 3858472
20. Proffit WR, Fields HW Jr, Sarver DM. Contemporary Orthodontics. 5th ed. St. Louis: Mosby Elsevier; 2013.
21. Alexander SA, Buschang PH, English JD, Gallerano RL. A study of bracket orientation and perceived aesthetic qualities of the smile. Angle Orthod. 2001;71(3):171-5. PMID: 11407765
22. Dellinger EL. A scientific assessment of the straight-wire appliance. Am J Orthod. 1978;73(3):290-9. PMID: 273447
23. Major TW, Carey JP, Nobes DS, Major PW. Mechanical effects of third-order movement in self-ligated brackets by the measurement of torque expression. Am J Orthod Dentofacial Orthop. 2011;139(1):e31-44. PMID: 21195256
24. Andrews LF. The straight wire appliance. Syllabus of philosophy and techniques. 2nd ed. San Diego: LA Wells; 1975.
25. Archambault A, Lacoursiere R, Badawi H, Major PW, Carey J, Flores-Mir C. Torque expression in stainless steel orthodontic brackets. A systematic review. Angle Orthod. 2010;80(1):201-10. PMID: 19852662
26. Sebanc J, Brantley WA, Pincsak JJ, Conover JP. Variability of effective root torque as a function of edge bevel on orthodontic arch wires. Am J Orthod. 1984;86(1):43-51. PMID: 6589966
27. Gioka C, Bourauel C, Zinelis S, Eliades T, Silikas N, Eliades G. Titanium orthodontic brackets: structure, composition, hardness and ionic release. Dent Mater. 2004;20(7):693-700. PMID: 15236942
28. Knox J, Jones ML, Hubsch P, Middleton J, Kralj B. An evaluation of the stresses generated in a bonded orthodontic attachment by three different load cases using the finite element method of stress analysis. J Orthod. 2000;27(1):39-46. PMID: 10790444
29. Kusy RP, Whitley JQ. Coefficients of friction for arch wires in stainless steel and polycrystalline alumina bracket slots. I. The dry state. Am J Orthod Dentofacial Orthop. 1990;98(4):300-12. PMID: 2220696
30. Lacoursiere RA, Nobes DS, Homeniuk DL, Carey JP, Badawi HM, Major PW. Measurement of orthodontic bracket tie wing elastic and plastic deformation by arch wire torque expression utilizing surface displacement analysis. J Biomech. 2010;43(3):397-403. PMID: 19896663
31. Middleton J, Jones M, Wilson A. The role of the periodontal ligament in bone modeling: the initial development of a time-dependent finite element model. Am J Orthod Dentofacial Orthop. 1996;109(2):155-62. PMID: 8638562
32. Nyashin Y, Rudakov R, Rusin N. Orthodontic biomechanics: a new look at the mechanical work of the dentition. Comput Methods Biomech Biomed Engin. 2005;8(5):303-9. PMID: 16298847
33. Pandis N, Strigou S, Eliades T. Maxillary incisor torque with conventional and self-ligating brackets: a prospective clinical trial. Orthod Craniofac Res. 2006;9(4):193-8. PMID: 17101028
34. Kapur R, Sinha PK, Nanda RS. Comparison of load transfer characteristics of titanium and stainless steel orthodontic wires. Am J Orthod Dentofacial Orthop. 1999;115(3):272-8. PMID: 10066975