Original Research
Dental Materials

# Deflection of tandem archwire in a specific self-ligating metal bracket system: an *in vitro* study

**Lourenço CATTANI**[(a)]
**Lourenço CORRER-SOBRINHO**[(b)]
**José Guilherme NEVES**[(b)]
**Heloísa VALDRIGHI**[(a)]
**Eduardo César Almada SANTOS**[(c)]
**Ana Rosa COSTA**[(a)]

[(a)]Fundação Herminio Ometto, Department of Orthodontics, Araras, SP, Brazil.

[(b)]Universidade Estadual de Campinas – Unicamp, Piracicaba Dental School, Department of Restorative Dentistry, Piracicaba, SP, Brazil.

[(c)]Universidade Estadual de Campinas – Unicamp, Piracicaba Dental School, Department of Health Sciences, Orthodontics and Pediatric Dentistry, Piracicaba, SP, Brazil.

**Declaration of Interests:** The authors certify that they have no commercial or associative interest that represents a conflict of interest in connection with the manuscript.

**Corresponding Author:**
Ana Rosa Costa
E-mail: anarosacosta@fho.edu.br

https://doi.org/10.1590/1807-3107bor-2023.vol37.0065

Submitted: April 4, 2022
Accepted for publication: November 21, 2022
Last revision: January 30, 2023

**Abstract:** The aim of this study was to quantify the force exerted by tandem archwires in a specific system of passive self-ligating bracket. Forty-eight thermo-activated nickel-titanium orthodontic archwires were separated into four groups (n = 12): G1 – two .014″ + .014″ round archwires; G2 – two .014″ + .016″ round archwires; G3 – .014″ x .025″ rectangular archwire; and. G4 – .016″ x .022″ rectangular archwire. Brackets were fixed onto teeth 1.5 to 2.5 using a device that represented the upper teeth, maintaining an interbracket distance of 6.0 mm. The deflection tests were performed using the structure representative of tooth 1.1 as support on the Instron testing machine at a speed of 2.0 mm/min. The archwires were evaluated at deflections of 0.5 mm, 1.0 mm, and 1.5 mm. The data were analyzed by a generalized linear model, considering values at different deflections as repeated measurements in the same experimental unit ($\alpha$ = 0.5%). At 0.5 mm, higher forces were observed in G2 and G3, which did not differ significantly ($p > 0.05$). The lowest force was observed in G4 ($p < 0.05$). At 1.0 mm and 1.5 mm, the highest force was observed in G3, followed by G4 and G2 ($p < 0.05$). The lowest force was observed in G1 ($p < 0.05$). In general, tandem archwires (same or different calibers) in a specific passive self-ligating bracket exerted lower force when compared with rectangular archwires.

**Keywords:** Orthodontic Wires; Materials Testing; Tooth Movement Techniques.

## Introduction

Self-ligating brackets have some advantages over conventional brackets such as reduction in frictional resistance, reduction in overall treatment time, and reduction of associated subjective discomfort.[1-4] Considering these advantages, it is not necessary to ligate the bracket to the archwire, either with rubber bands or metal braces, thus reducing chair time.[1]

Additionally, in the initial phases of treatment, the archwire is free in the bracket slot, considerably reducing friction, an advantage reflected mainly in sliding mechanics or in the initial phases of alignment and leveling when dental crowding is present.[5-6] However, due to this gap between passive self-ligating brackets and leveling archwires, greater control over some tooth movements is required in the initial phases of alignment and leveling, such as torque control and rotation.[7-10]

Between a 0.014″ round alignment archwire and a passive bracket, there is a clearance of approximately 10 degrees, while on a conventional bracket, there is no clearance between the archwire and the bracket.[10] To address this limitation in the initial phase of orthodontic treatment, some changes in the clinical protocol have been adopted, such as the use of metal ligatures, rectangular archwires in the initial phases of treatment and, recently, the use of two overlapping round archwires (tandem archwire) to better fill the bracket slot, with greater control over orthodontic movement.[7,9,10]

Specifically, in the Damon® or Smartclip® system (passive ligating bracket), alignment and leveling is performed in two phases. In the first phase, with the use of .014″ or .016″ superelastic round archwires, the alignment is almost complete. In the second phase, alignment and leveling is finished with .014″ x .025″ or .016″ x .025″ superelastic rectangular archwires.[11,12] On the other hand, the Smartclip® system recommends the use of two superelastic round archwires: .014″ and .016″ for .022″ x .028″ bracket slots or two .014″ for 018″ x .028″ bracket slots.[10] Such a change in the protocol would provide an almost complete filling of the bracket slot, but with lighter forces in relation to rectangular archwires. A previous study[7] has shown that bracket slot dimensions of Damon 2 were relatively more consistent than those of SmartClip®, although the torque of both brackets followed a similar pattern. In addition, both brackets have a closing system that changes the open slot into a tube.[13]

Thus, it is important to know the properties of the materials used in orthodontic practice, as choices can be made based on scientific studies and not only on the experience of the professional or on the clinical experience of authors, which would provide low clinical evidence for decision-making. Another previous study has shown the technique, describing the sequence of clinical cases. However, to date, there is no study with a laboratory trial comparing the forces exerted by this system with those of rectangular archwires.[10] Because of this gap in the current literature on the mechanical properties of this technique routinely used by orthodontists, it is therefore important and necessary to conduct this study.

The objective of the present study was to quantify the force exerted by overlapping round wires (tandem archwire) in a system of passive self-ligating metal brackets, comparatively to rectangular archwires. The null hypothesis of the study was that the use of two overlapping round archwires would apply a lighter force on the teeth than would rectangular archwires for dental alignment and leveling in a specific self-ligating bracket.

## Methodology

The sample size was previously calculated with a power of at least 0.80 and a significance level of 5%, which required 12 specimens in each group. Forty-eight orthodontic archwires were tested with a set of passive Smartclip® self-ligating brackets (3M ESPE, St. Pauls, MN, USA) MBT prescription, slot .022″ x .028″ and separated into four groups (n=12): G1 - two thermo-activated nickel-titanium round archwires of the same caliber (.014″ + .014″); G2 - two thermo-activated nickel-titanium round archwires of different caliber (.014″ + .016″); G3 - thermo-activated nickel-titanium rectangular archwire (.014″ x .025″); and G4 - thermo-activated nickel-titanium rectangular archwire (.016″ x .022″). Only 3M ESPE archwires were used.

Deflection of the orthodontic wire was performed in a clinical simulation device representing all 10 teeth in the maxillary arch. In an acrylic device representing the upper teeth (Figure 1A), the brackets of teeth 1.5 to 2.5 were fixed with the aid of a .021″ x .025″ archwire in the .022″ x .028″ slot to ensure that the brackets were passively bonded with a cyanoacrylate-based adhesive (Superbond®, Loctite, Henkel Ltda., São Paulo, Brazil).[14-16] The interbracket distance was maintained at 6 mm, which represents the average distance between the tie-wings of brackets, considering the average size of teeth and brackets in the mesiodistal direction.[17] The device was immersed in a container of deionized

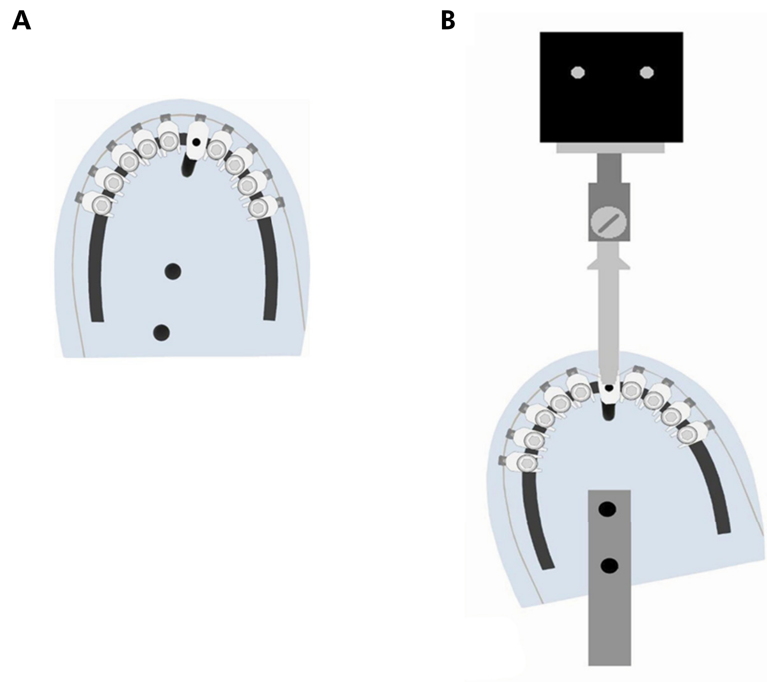


**Figure.** A. Acrylic device representing the upper teeth with the brackets attached to teeth 1.5 to 2.5 + test archwires. B. Diagram representing the archwire deflection test on the universal test machine, in which dental element 1.1 served as support on the Instron testing machine coupled to a 10 N load cell. All blocks were fixed by means of screws inserted at the bottom of the acrylic resin plate, except for the maxillary right central incisor (1.1), thus allowing buccolingual movement.

water and maintained therein at a temperature of 36 ± 1°C. Before each test, the load cell was adapted and calibrated. The deflection tests were performed in the palatine-buccal direction using the representative tooth structure 1.1 as support on Instron 3342 universal testing machine (Norwood, City, USA) coupled with a 10 N load cell at a speed of 2.0 mm/min. The archwires were evaluated at the following deflections: 0.5 mm, 1.0 mm, and 1.5 mm (Figure 1B).

### Statistical analysis

Exploratory and descriptive analysis of the data indicated that they did not meet the assumptions of an analysis of variance. A generalized linear model was then adjusted, considering the measurements at different deflections (0.5 mm, 1 mm, and 1.5 mm) as repeated measurements in the same experimental unit. The analyses were performed using the SAS software program (SAS Institute Inc., Cary, CityUSA, Release 9.2.2010), considering a 5% significance level.

## Results

Table shows that the deactivation force increased significantly with the increase in deflection ($p < 0.05$). At 0.5 mm, higher forces were observed in the thermo-activated 0.014″ x .025″ archwire and in the 0.014″ tandem archwire superimposed on the .016″ archwire, with statistically higher rates than the others ($p < 0.05$). No statistical difference was observed between these two archwires ($p > 0.05$). The lowest force was observed in the thermo-activated 0.016″ x 0.022″ archwire ($p < 0.05$). At 1.0 mm and 1.5 mm, the greatest force was observed in the thermo-activated .014″ x .025″ archwire, which was statistically superior to thermo-activated 0.016″ x 0.022″ archwires, 0.014″ tandem archwire superimposed on the 0.016″ archwire, and 0.014″ tandem archwire superimposed on the 0.014″ archwire ($p < 0.05$). The lowest force was observed in the 0.014″ tandem archwire superimposed on the 0.014″ archwire ($p < 0.05$).

**Table.** Mean (standard deviation) of the force (cN) as a function of the type of archwire and deflection. Means followed by different letters (uppercase letters in the row and lowercase letters in the column) differ from each other ($p < 0.05$).

| Archwire | Deflection | | |
|---|---|---|---|
| | 0.5 mm | 1.0 mm | 1.5 mm |
| 1) .014″ + .014″ | 154.8 (5.9) Cb | 285.6 (10.6) Bd | 455.2 (43.9) Ad |
| 2) .014″ + .016″ | 210.9 (28.1) Ca | 313.2 (34.2) Bc | 509.0 (60.3) Ac |
| 3) .014″ x .025″ | 218.4 (13.5) Ca | 468.6 (33.3) Ba | 915.5 (35.0) Aa |
| 4) .016″ x .022″ | 129.2 (11.7) Cc | 335.4 (24.1) Bb | 744.1 (26.6) Ab |

P (archwire) <0.0001; p (deflection) < 0.0001; p (archwire x deflection) < 0.0001. 1) 0.014″ round archwire superimposed on the 0.014″ (tandem archwire); 2) 0.014″ round archwire superimposed on the 0.016″ (tandem archwire); 3) 0.014″ x 0.025″ rectangular thermoset archwire; and 4) 0.016″ x 0.22″ rectangular thermoset archwire.

## Discussion

In the first stages of alignment in passive self-ligating systems, there is a gap between the orthodontic archwire and the brackets. This gap allows freedom of movement, considerably reducing the friction between the archwire and the bracket in relation to the conventional bonding system.[18] This freedom of movement is beneficial in the initial phase of treatment, but in the second phase, it is desirable that the space be as small as possible in order to fit as much as possible the prescription of the orthodontic bracket, allowing alignment, leveling, and total correction of rotated teeth, in addition to torque control.[11] Although a simplified three-point bending test would be recommended for archwire characterization at the middle point, allowing passive unload; in the present study, the elastic deflection test was chosen because it is clinically closest to the orthodontists' interests because that is what they do when adapting an archwire to the patient's teeth.[15,16,19]

Recently, a study has compared the efficiency of alignment (correction rate in mm/day) in the use of tandem archwires associated with self-ligating brackets, self-ligating brackets associated with standard archwire sequencing, and conventional apparatus with conventional connection, and the conclusion was that there was no statistically significant difference between the evaluated groups.[20] However, the archwire sequencing used in this recent study[20] resulted in too many changes of archwires in the tandem group compared to the recommended clinical protocol, which could lead to an increase in treatment time and automatically reduce the rate of correction, given that the rate is calculated in mm/day. One of the benefits of the tandem system, in addition to improving the correction of rotated teeth, is to reduce the number of archwire changes rather than to increase it, a fact that may have impaired the evaluation of the system efficiency.

Note that ISO 15841[21] recommends the evaluation of orthodontic wire force at the deflections of 0.5 mm, 1 mm, 2 mm, and 3 mm. However, in a previous pilot test, it was observed that at 2 mm and 3 mm, the force exceeded the limit of the 10 N load cell. Such force magnitudes are not clinically applicable because they exceed the appropriate value for tooth movement[22]. Moreover, the archwires evaluated in this study are used in a phase in which only small movements have to be performed for the alignment.[10,11] Therefore, given this limitation, the methodology was adapted and the archwires were evaluated at 0.5 mm, 1.0 mm, and 1.5 mm.

The null hypothesis of the present study was partially accepted because the use of two overlapping round archwires applied a lighter force to the teeth in relation to rectangular archwires for dental alignment and leveling in a specific passive self-ligating metal bracket (Smartclip®). In the present study, at 1.0 mm and 1.5 mm, the highest forces were observed in 0.014″ x 0.025″ and 0.016″ x 0.022″ rectangular archwires, respectively, followed by 0.014″ + 0.016″ tandem archwires (superimposition of round archwires with different caliber) and 0.014″ + 0.014″ tandem archwires (superimposition of round archwires with the same caliber).

The smallest force exerted by 0.014″ + 0.014″ tandem archwires correlates with the smallest cross-sectional area of these archwires. On the other hand, at 0.5 mm, greater force was observed in 0.014″ x 0.025″ rectangular and 0.014″ + 0.016″ tandem archwires, which did not differ statistically from each other, followed by 0.014″ + 0.014″ tandem archwires and 0.016″ x 0.022″ rectangular archwires. This difference in the 0.016 x .022″ archwire cannot be explained by the cross-sectional area because the area of the 0.014″ x 0.014″ tandem archwire is smaller. It can be speculated, however, that this difference is due to the friction between the archwires and the bracket walls, which would make it difficult to release forces in more "filled" bracket slots and would facilitate the release of forces from 0.016″ x 0.022″ archwires in a 0.022″ x 0.028″ bracket slot because of the greater clearance between the archwire/bracket and greater freedom of movement.

The mechanical behavior of metal alloys follows a load/deflection graph according to Hooke's law,[23] where the greater the distance of deflection, the greater the accumulated force. The results obtained in this study are in accordance with Hooke's law because the greater the deflection of the archwire, the greater the force released in all samples. The mechanical properties of the archwires were not altered by the use of two archwires in the same slot and by the interaction between the bracket and the archwire, that is, the deformation was proportional to the tension applied to the archwire, as NiTi wires have a typical pseudoelastic behavior, in which the crystal structure changes from austenite to martensite and vice versa as a response to a load change or to temperature.[19]

In this sense, in rectangular archwires of the same cross-sectional area, resistance increases according to the increase in archwire width. Thus, considering that 0.016″ x 0.022″ and 0.014″ x 0.025″ archwires have similar cross-sectional areas at deflections in the occlusal-gingival direction in the 0.022″ x 0.028″ slot, a 0.016″ x 0.022″ archwire would release more force in relation to a .014″ x .025″ archwire.[24] However, in the present study, the deflection of the archwire was performed in the palatine-buccal direction, and the greatest force was observed for the 0.014″ x 0.025″ rectangular archwire at all deflections in relation to the 0.016″ x 0.022″ rectangular archwire, as explained above.

An important factor for the selection of an orthodontic archwire is the magnitude of the force that will be exerted on the teeth. More intense orthodontic forces cause more areas of overcompression in the periodontal ligament than do light forces, generating side effects such as excessive pain,[25] root resorptions of greater magnitude,[26] and uncontrolled tipping,[22] among others. Thus, forces with lighter intensities are desired during orthodontic treatment because they allow movement with fewer side effects. According to Proffit,[27] the force magnitude should not exceed 2-3 N, corresponding to a biological corridor.

Low-magnitude forces should be used in orthodontic mechanics whenever possible. In this study, the use of the tandem archwire proved to be advantageous compared to the use of rectangular archwires because it exerted lower-magnitude forces at 1.0 mm and 1.5 mm, although the 0.016″ x 0.022″ rectangular archwire exerted less force at 0.5 mm than did 0.014″ + 0.014″ and 0.014″ + 0.016″ tandem archwires (Table 1). This difference can be explained by the friction between the bracket slot and the archwires,[18] as the archwires provide a complete filling of the bracket slot in the tandem archwire technique, unlike the 0.016″ x 0.022″ rectangular archwire in a 0.022″ x 0.028″ slot, in which the archwire can work more freely without excessive contact with the bracket walls. Additionally, smaller-diameter archwires exert smaller forces, as they are not completely pressed against the slot [28] because of the flexible NiTi pointed clips in the SmartClip® used in the present study.[19]

Note that, although the 0.016″ x 0.022″ rectangular archwire exerted less force at 0.5 mm than did the tandem archwires (same or different caliber), with a force between 1.3 and 2.2 N, all tested groups exhibited a force within the range and below 3N.[27] The friction between the archwire and the bracket and between the archwire and the ligation method may adversely affect the behavior of tooth movement. Keeping this in mind, archwire materials (stainless steel, NiTi, and CuNiTi), geometry (round *vs* rectangular) and cross-sectional diameter, bracket design (conventional, active, or passive self-ligating), material and slot dimensions, and archwire ligation system (metallic or elastomeric ligature in conventional brackets and type and composition of self-ligating bracket clips) are examples of factors that could alter friction and, consequently, torque application.[7,13,19, 24, 28,29]

Also of note is a previous study[30] that evaluated dental resorption after leveling with conventional and self-ligating brackets, using standard and tandem archwire sequences, and revealed a higher dental resorption rate in the group that used the alignment sequence, including the tandem archwire.[30] The archwires were changed at intervals of 1 to 1.5 months. However, the archwire replacement protocol in the tandem group had an extra set of archwires in the treatment, which is contrary to the recommendation by Sondhi and Kalha,[10] whose aim was to reduce the number of archwires during orthodontic treatment. It is worth noting that the reduction in the number of archwires tends to reduce the duration of the alignment and leveling phase[2] which, combined with less release of forces, according to the results of this study, could perhaps reduce potential dental resorption. Reducing the time of the alignment phase would also provide greater time availability for the treatment completion phase.

Therefore, reducing the number of archwires initially recommended by the literature,[10] combined with the release of lower intensity forces in the alignment and leveling phase, seems to be a very interesting alternative in clinical practice using Smartclip® passive self-ligating brackets. Further *in vitro* and *in vivo* studies are needed to elucidate the combined use of round archwires of different calibers associated with different self-ligating brackets with different slot depths in relation to tooth resorption, friction, force release, and biofilm accumulation.

## Conclusion

The use of two round archwires (tandem archwire) in the same slot in a specific passive self-ligating bracket (SmartClip®) showed lower force release in relation to rectangular archwires, employed in the dental alignment phase, except at 0.5 mm, in which the 0.16 x 0.22" nickel-titanium archwire exerted less force than did the tandem system. Selection of lower forces with lighter intensities without sacrificing efficiency of the orthodontic treatment should be preferred to overcome negative side effects.

## References

1. Chen SS, Greenlee GM, Kim JE, Smith CL, Huang GJ. Systematic review of self-ligating brackets. Am J Orthod Dentofacial Orthop. 2010 Jun;137(6):726.e1-18. https://doi.org/10.1016/j.ajodo.2009.11.009
2. Fleming PS, Johal A. Self-ligating brackets in orthodontics: a systematic review. Angle Orthod. 2010 May;80(3):575-84. https://doi.org/10.2319/081009-454.1
3. Atik E, Akarsu-Guven B, Kocadereli I, Ciger S. Evaluation of maxillary arch dimensional and inclination changes with self-ligating and conventional brackets using broad archwires. Am J Orthod Dentofacial Orthop. 2016 Jun;149(6):830-7. https://doi.org/10.1016/j.ajodo.2015.11.024
4. Dehbi H, Azaroual MF, Zaoui F, Halimi A, Benyahia H. Therapeutic efficacy of self-ligating brackets: A systematic review. Int Orthod. 2017 Sep;15(3):297-311. https://doi.org/10.1016/j.ortho.2017.06.009
5. Voudouris JC. Interactive edgewise mechanisms: form and function comparison with conventional edgewise brackets. Am J Orthod Dentofacial Orthop. 1997 Feb;111(2):119-40. https://doi.org/10.1016/S0889-5406(97)70208-7
6. Harradine N. Self-ligating brackets increase treatment efficiency. Am J Orthod Dentofacial Orthop. 2013 Jan;143(1):10-8. https://doi.org/10.1016/j.ajodo.2012.10.011
7. Badawi HM, Toogood RW, Carey JP, Heo G, Major PW. Torque expression of self-ligating brackets. Am J Orthod Dentofacial Orthop. 2008 May;133(5):721-8. https://doi.org/10.1016/j.ajodo.2006.01.051
8. 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 Jun;30(3):233-8. https://doi.org/10.1093/ejo/cjn005

9. Pesce RE, Uribe F, Janakiraman N, Neace WP, Peterson DR, Nanda R. Evaluation of rotational control and forces generated during first-order archwire deflections: a comparison of self-ligating and conventional brackets. Eur J Orthod. 2014 Jun;36(3):245-54. https://doi.org/10.1093/ejo/cjr119
10. Sondhi A, Kalha AS. The tandem archwire concept with self-ligating brackets. J Clin Orthod. 2014 Apr;48(4):221-30.
11. Birnie D. The damon passive self-ligating appliance system. Semin Orthod. 2008;14(1):19-35. https://doi.org/10.1053/j.sodo.2007.12.003
12. Miles PG. SmartClip versus conventional twin brackets for initial alignment: is there a difference? Aust Orthod J. 2005 Nov;21(2):123-7.
13. Brauchli LM, Steineck M, Wichelhaus A. Active and passive self-ligation: a myth? Part 1: torque control. Angle Orthod. 2012 Jul;82(4):663-9. https://doi.org/10.2319/062011-673.1
14. Gurgel JA, Kerr S, Powers JM, LeCrone V. Force-deflection properties of superelastic nickel-titanium archwires. Am J Orthod Dentofacial Orthop. 2001 Oct;120(4):378-82. https://doi.org/10.1067/mod.2001.117200
15. Francisconi MF, Janson G, Henriques JF, Freitas KM. Evaluation of the force generated by gradual deflection of orthodontic wires in conventional metallic, esthetic, and self-ligating brackets. J Appl Oral Sci. 2016;24(5):496-502. https://doi.org/10.1590/1678-775720150405
16. Francisconi MF, Janson G, Henriques JF, Freitas KM, Francisconi PA. Evaluation of the force generated by gradual deflection of 0.016-inch NiTi and stainless steel orthodontic wires in self-ligating metallic and esthetic brackets. J Clin Exp Dent. 2019 May;11(5):e464-9. https://doi.org/10.4317/jced.55698
17. Fernandes TM, Sathler R, Natalício GL, Henriques JF, Pinzan A. Comparison of mesiodistal tooth widths in Caucasian, African and Japanese individuals with Brazilian ancestry and normal occlusion. Dental Press J Orthod. 2013;18(3):130-5. https://doi.org/10.1590/S2176-94512013000300021
18. Burrow SJ. Friction and resistance to sliding in orthodontics: a critical review. Am J Orthod Dentofacial Orthop. 2009 Apr;135(4):442-7. https://doi.org/10.1016/j.ajodo.2008.09.023
19. Reznikov N, Har-Zion G, Barkana I, Abed Y, Redlich M. Influence of friction resistance on expression of superelastic properties of initial NiTi wires in "reduced friction" and conventional brackets systems. J Dent Biomech. 2010;2010(1):613142. https://doi.org/10.4061/2010/613142
20. Bhardwaj P, Sonar S, Batra P. Alignment efficiency of standard versus tandem wire mechanics using conventional and self-ligating brackets: a pilot study. J Indian Orthod Soc. 2017;51(2):103-9. https://doi.org/10.4103/jios.jios_208_16
21. International Organization for Standardization. ISO 15841: Dentistry: wires for use in orthodontics. Berlin: International Organization for Standardization; 2006.
22. Theodorou CI, Kuijpers-Jagtman AM, Bronkhorst EM, Wagener FA. Optimal force magnitude for bodily orthodontic tooth movement with fixed appliances: a systematic review. Am J Orthod Dentofacial Orthop. 2019 Nov;156(5):582-92. https://doi.org/10.1016/j.ajodo.2019.05.011
23. Burstone CJ. Physics and clinical orthodontics: 100 years ago and today. Am J Orthod Dentofacial Orthop. 2015 Mar;147(3):293-4. https://doi.org/10.1016/j.ajodo.2014.12.011
24. Arreghini A, Lombardo L, Mollica F, Siciliani G. Load deflection characteristics of square and rectangular archwires. Int Orthod. 2016 Mar;14(1):1-14. https://doi.org/10.1016/j.ortho.2015.12.011
25. Luppanapornlarp S, Kajii TS, Surarit R, Iida J. Interleukin-1beta levels, pain intensity, and tooth movement using two different magnitudes of continuous orthodontic force. Eur J Orthod. 2010 Oct;32(5):596-601. https://doi.org/10.1093/ejo/cjp158
26. Paetyangkul A, Türk T, Elekdağ-Türk S, Jones AS, Petocz P, Cheng LL, et al. Physical properties of root cementum: Part 16. Comparisons of root resorption and resorption craters after the application of light and heavy continuous and controlled orthodontic forces for 4, 8, and 12 weeks. Am J Orthod Dentofacial Orthop. 2011 Mar;139(3):e279-84. https://doi.org/10.1016/j.ajodo.2010.07.021
27. Chapter 9. In: Proffit WR, Fields HW. Contemporary orthodontics. St. Louis: Mosby; 2000.
28. Nucera R, Gatto E, Borsellino C, Aceto P, Fabiano F, Matarese G, et al. Influence of bracket-slot design on the forces released by superelastic nickel-titanium alignment wires in different deflection configurations. Angle Orthod. 2014 May;84(3):541-7. https://doi.org/10.2319/060213-416.1
29. Tran B, Nobes DS, Major PW, Carey JP, Romanyk DL. Research paper: the three-dimensional mechanical response of orthodontic archwires and brackets in vitro during simulated orthodontic torque. J Mech Behav Biomed Mater. 2021 Feb;114:104196. https://doi.org/10.1016/j.jmbbm.2020.104196
30. Singh A, Batra P, Singla A, Sonar S. Evaluation of external apical root resorption postleveling and alignment with self-ligating and conventional appliance (MBT) using standard and tandem wires: a prospective randomized clinical trial. J Indian Orthod Soc. 2018;52(3):179-83. https://doi.org/10.4103/jios.jios_118_17