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Roller Bracket allows the friction reduction compared to the conventional bracket - a finite element analysis

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Aim: This study aimed to present the Roller Bracket, an invention for reducing the friction between the archwire and the bracket slot floor/edges.

Methods: The Roller Bracket considers the incorporation of sliding spheres on the intermediate bracket base. The geometry was determined and analyzed by constructing a three-dimensional computer-aided design (CAD) model using SolidWorks software. The morphology of the models was based on conventional brackets and archwires available on the market. Then, the created structure was discretized in finite elements using an Abaqus software. The elements were defined by coordinates in space (nodes) and in interconnected form functions. In these models, linear triangular (CPS3) and square linear (CPS4R) elements were used. A convergence analysis allowed defining the ideal mesh.

Results: When the Roller Bracket test was performed considering the presence of a lubrication by the saliva or by a solid material, the frictional force reached a value of 1.3 g, which represents a reduction of 41% in relation to the Roller Bracket without lubrication and 48% in relation to the conventional bracket.

Conclusion: The present study demonstrated that the design of the Roller Bracket adds several advantages over the state of the art and may lead to more satisfactory results in orthodontic treatments considering the reduction of friction during the sliding mechanics.

Uniterms: orthodontic brackets; orthodontic friction; orthodontics; technology, dental; tooth movement techniques.

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INTRODUCTION

In clinical terms, to move a tooth to a desired position, the force applied to the arch should exceed the friction component at the interface among bracket, archwire and/or ligatures.[1] In this sense, a study has shown that friction between the bracket and the archwire can lead to the loss of more than 50% of the initially applied orthodontic force, resulting in the decrease or even inhibition of the desired movement.[2] Therefore, more force is required to overcome the frictional component at the archwire ligature/bracket slot interface and to move the teeth.[3] The paradoxical point is that greater forces can lead to biological impairment, such as root resorption[4] while low forces might reduce the risk of root resorption[5] and increase patient comfort[6] as well.

Friction is considered a small part of the resistance to movement as a bracket slides

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along an archwire.[7] According to Kusy and Whitley [8] friction, binding and notching are the three components of the called "resistance to sliding". Friction can be static or kinetic and is due to contact of between the archwire and bracket surfaces.[7] Friction originates from electromagnetic forces between atoms[7] and has a multifactorial nature, derived from a variety of mechanical and biological factors.[1,9] The existing angulation between the bracket and the archwire,[10] the size, thickness and materials of the archwires,[11] the ligatures,[12] the width of the bracket slot and the materials of the brackets,[13] surface roughness,[14] the saliva[15] as well as the accumulation of debris in the appliance[2] are examples of factors related to increased friction during orthodontic tooth movements.

Diverse researchers have focused on developing strategies to reduce friction during orthodontic tooth movement. Attempts have included modifications to the bracket[16] and archwire[17] materials, addition of coatings or other treatment on the surface of the materials,[18,19] changes in the geometry of the bracket slots,[20] and use of low friction elastomeric ligatures.[21] In addition, the introduction of the self-ligating bracket system[22] was considered the most claimed step towards the reduction of friction between the bracket and the archwire. However, systematic reviews and meta-analysis have shown that there is insufficient scientific evidence to determine the superiority of self-ligating versus conventional brackets.[23,24]

A critical evaluation of the main attempts to reduce friction during sliding mechanics reveals that they run into limitations. Also, the various patents deposited in different countries [Takemoto, 2009 (US2011151390); Shin Woo, 2009 (WO2011019146); Duran Von, 2009 (WO2010103153); Queiroz, 2006 (MU8601463-3); Giraldo, 2006 (MX2008014761); Wolf, 2006 (WO2007115268); Park, 2006 (KR100741254); Vigolo, 2003 (US2006246392); Salich, 2005 (US2007184399); Nucera, 2004 (US2008014544); Brusse, 2000 (WO0217812); Brown, 1999 (US6168429; Gagin, 1992 (WO9400072); Fukuhara, 1989 (JP3012148)] refer only to the friction between the archwire and the materials that hold the archwire within the bracket slot.

Considering the state of the art, it is observed that the mechanisms developed to reduce friction caused by compression of the archwire against the bracket slot floor rely, mainly, on three systems: slot closure system (self-ligating brackets), low-friction elastomeric ligatures, archwire and/or bracket surfaces coating. Hence, a fourth and different approach could, in fact, lead to more satisfactory results considering the reduction of friction during sliding mechanics.

Therefore, the aim of the present study was to present the Roller Bracket, an invention for reducing the friction between the archwire and the bracket slot floor/edges and to compare the friction between the Roller Bracket and the conventional bracket using the finite element analysis (FEA).

MATERIAL AND METHODS

THE ROLLER BRACKET

The present invention refers to a new model of orthodontic bracket, which characteristics aim at reducing the friction during orthodontic tooth movement. The patent was registered at the National Institute of Industrial Property (INPI) under the number 1101640.

The Roller Bracket introduces a new approach and specifically considers an incorporation of sliding spheres (floating) on the intermediate bracket base so that the surfaces of the spheres are in direct contact with the archwire. Figures 1 and 2 show the structure of the Roller Bracket, which has a base with retentions for bonding to tooth surface, an intermediate base, which houses two spheres to reduce friction, one slot, two gingival tie-wings and two occlusal tie-wings. A sphere for friction reduction is located on the mesial edge of the bracket and the other on the distal edge, so to form the respective mesial and distal outer walls of the intermediate bracket base. Since a conventional elastomeric ligature undergoes stretching and rests on the archwire by pressing it against the bracket slot, two points of resistance to tooth movement are established: the first refers to the contact between the archwire and the conventional elastomeric ligature and the second to the contact of the archwire with the bracket slot floor/edges.

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Figure 1. Roller Bracket in front perspective. 1: Bracket base; 2: Intermediate base; 3: Floating sphere; 4: Slot; 5: Gingival tie-wings; 6: Occlusal tie-wings.

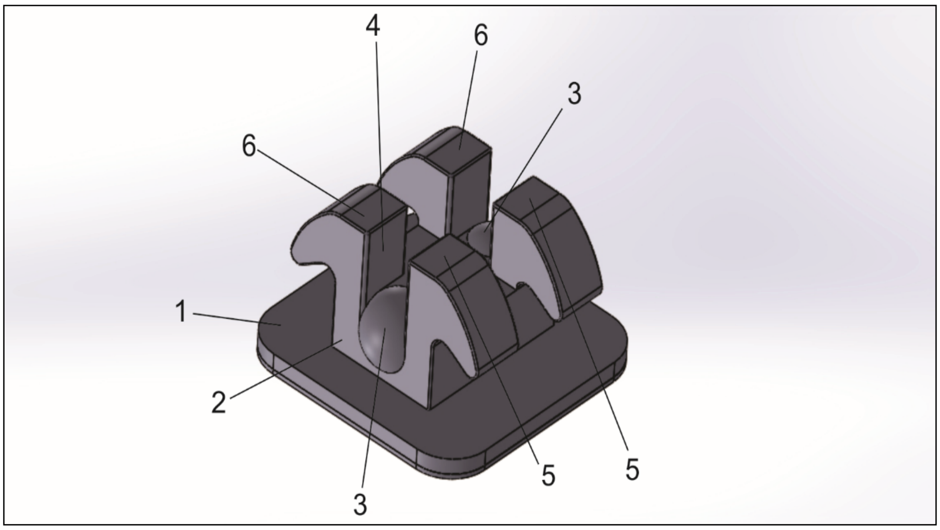
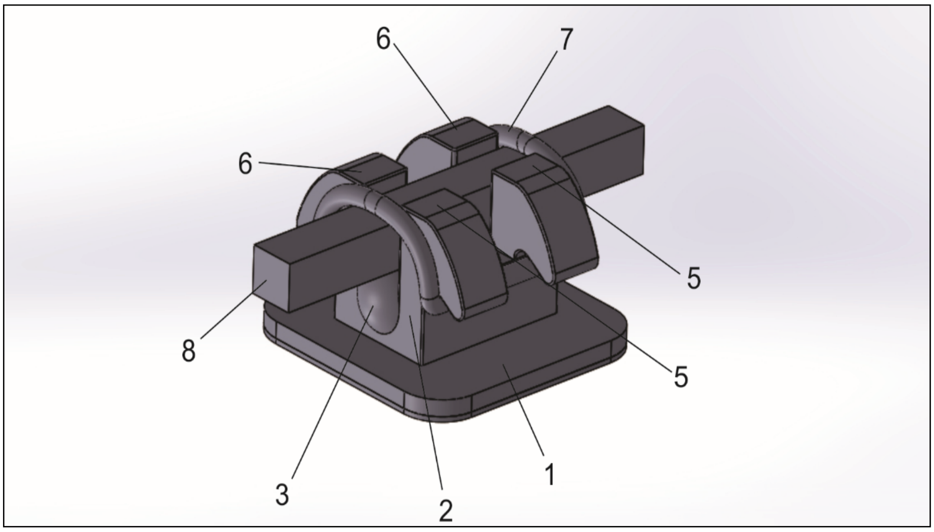


Figure 2. Roller Bracket in front perspective associated with the wire and conventional elastomeric ligature. 1: Bracket base; 2: Intermediate base; 3: Floating sphere; 4: Slot; 5: Gingival tie-wings; 6: Occlusal tie-wings; 7: Conventional elastomeric ligature; 8: Orthodontic wire.



MECHANISM OF ACTION

The mechanism of action of the Roller Bracket lies in the fact that the spheres are “floating”, so that they can rotate freely within the intermediate base when in contact with the archwire in situations involving friction. Moreover, the surfaces of the spheres will act as substitutes of the slot floor, so as to eliminate the surface roughness of the material used for bracket manufacture, another factor that increases friction. In other words, the archwire will be compressed against the surface of the spheres, which have greater ease of handling in virtue they are relatively free within the intermediate base, having patient’s own saliva as a lubricant factor. Analogously, the sliding spheres of the Roller Bracket mechanically resemble the ball located on a tip of a ballpoint pen, which once compressed on a surface of the paper sheet, rotates, dissipating a force and dispensing ink.

In a theoretical perspective, the Roller Bracket adds several advantages over the state of the art, including: a) reduces the friction between the archwire and the bracket slot floor, favoring the sliding mechanics; b) promotes friction reduction both in the early stages of orthodontic treatment, with smaller-caliber archwires, as in the intermediate and final stages, with rectangular and larger-caliber archwires; c) can be applied to brackets made of different materials such as sapphire, porcelain, steel, polycarbonate, resin and plastic; d) can be applied to both conventional and self-ligating brackets; e) can be applied to lingual brackets; f) requires the application of lower force magnitude, favoring the tooth movement and preserving the periodontal structures, besides of reducing the pain and the risk of root resorption; g) allows the reduction of the number of appointments, the device settings and the total time of orthodontic treatment; h) can be applied to other orthodontic appliances involved in tooth movement such as molar tubes; i) does not interfere with torque control; j) can be applied in different techniques and prescriptions, such as Edgewise, straight wire, Rickets, Alexander and MBT; l) takes the patient's own saliva as a lubricant factor to favor the movement (rotation) of the spheres, favoring directly the dissipation of friction.

EXPERIMENTAL MODEL

To obtain a theoretical model, the geometric characteristics and properties of the materials used in the conventional bracket and in the Roller Bracket, as well as in the archwire were defined. Initially, geometry was determined and analyzed by constructing a three-dimensional computer-aided design (CAD) model using SolidWorks software (SolidWorks Corporation, MA, USA). The morphology of the models was based on conventional brackets and archwires available on the market (Figures 3 and 4). Figure 5 presented the Roller Brackets with the measurements. Then, the created structure was discretized in finite elements using a specific software (Abaqus®, Dessault Systèmes, France). The elements were defined by coordinates in space (nodes) and in interconnected form functions. In these models, linear triangular (CPS3) and square linear (CPS4R) elements were used. A convergence analysis allowed defining the ideal mesh.

To verify the interaction between the analyzed bodies (archwire, sliding spheres and ligatures), an analysis with the inclusion of contact between the models of each body was necessary, thus enabling the verification of interaction efforts such as normal and frictional forces. Initially, the conventional bracket was modeled using the above-mentioned Abaqus® software and, from this, the Roller Bracket was modeled. Thus, the Roller Bracket was constructed as follows: a base with retentions for bonding to tooth surface; an intermediate base, housing two spheres for friction reduction; one slot; two gingival tie-wings; and two occlusal tie-wings. The spheres for friction reduction were located at the mesial and distal outer walls of the bracket so as to form the respective mesial and distal outer walls of the intermediate bracket base, besides of representing two points of support for the archwire.

Figure 3. Conventional bracket in front perspective. 1: Bracket base; 2: Intermediate base; 3: Gingival tie-wings; 4: Occlusal tie-wings; 5: Slot.

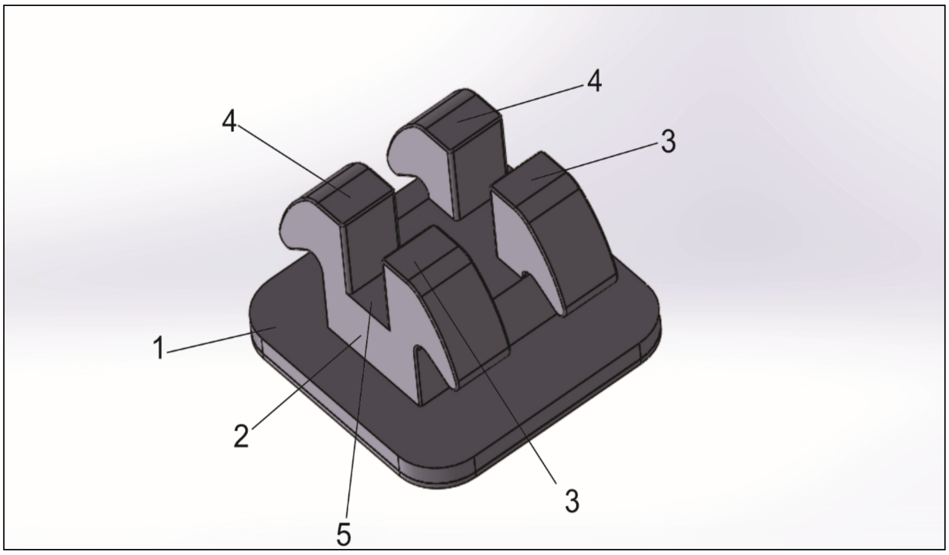


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Figure 4. Conventional bracket in front perspective associated with the wire and conventional elastomeric ligature. 1: Bracket base; 2: Intermediate base; 3: Gingival tie-wings; 4: Occlusal tie-wings; 5: Slot; 6: Orthodontic wire; 7: Conventional elastomeric ligature.

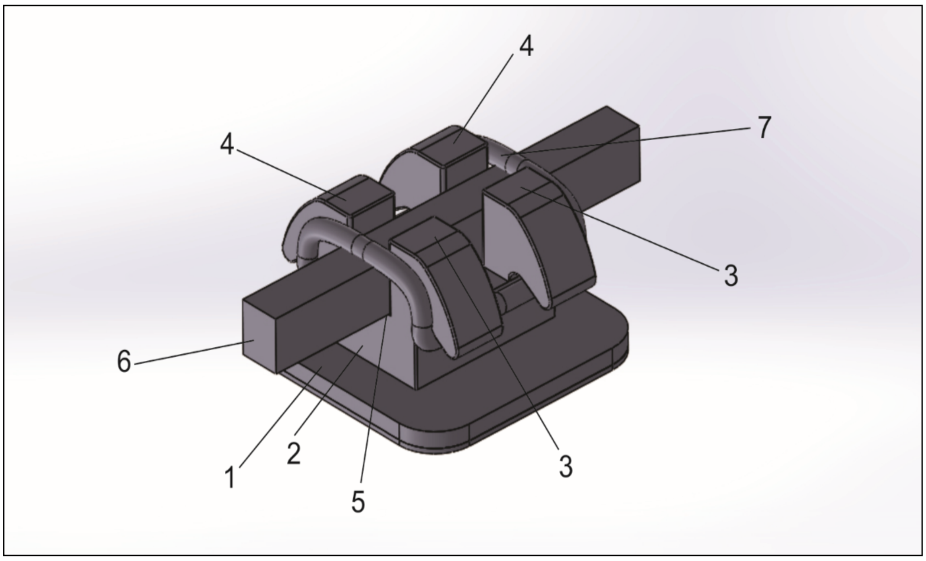
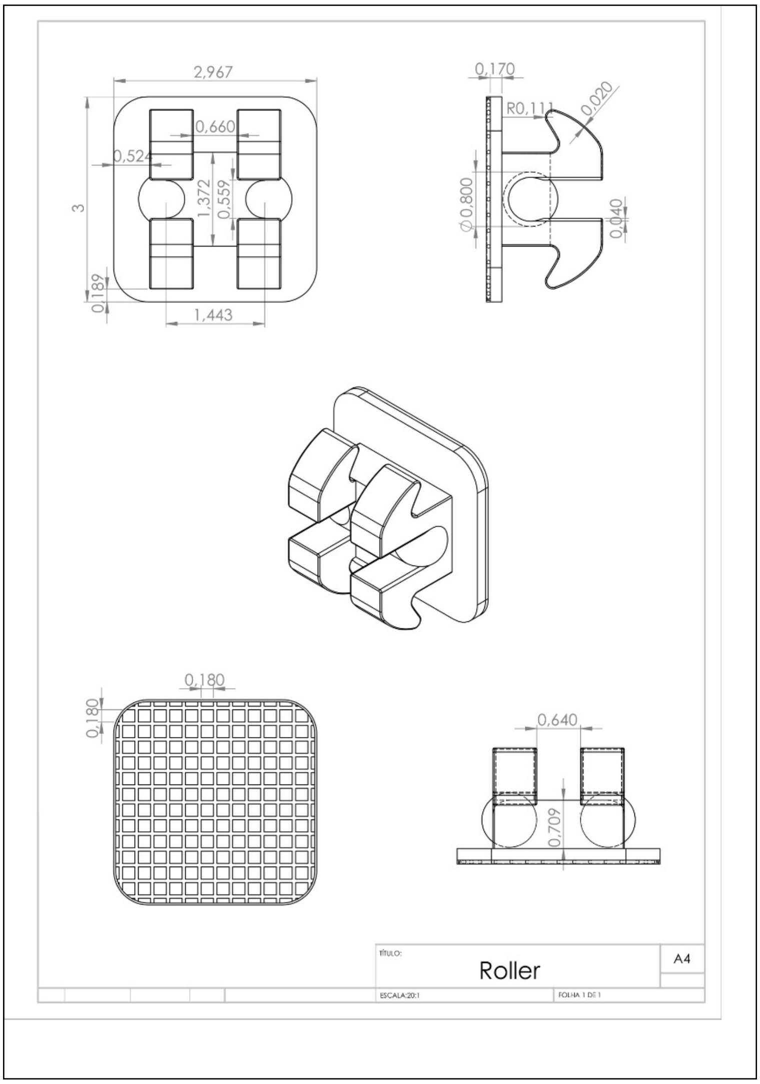


Figure 5. Roller Bracket with measurements in millimeters (mm).



PROPERTIES OF THE EXPERIMENTAL MODEL

The mechanical properties of the orthodontic materials used in this study were based on studies available in the literature.[10,25,26] These properties were the input data for the numerical model that was based on FEA method. The structures that make up the model composed of metallic materials have identical characteristics and values for the mechanical properties, considering that all materials were made up of stainless steel (Conventional bracket, Roller Bracket and archwire). The orthodontic brackets are produced in stainless steel and have defined properties for the modulus of elasticity for the Poisson coefficient.[11] For the sliding spheres, the same properties were used (Table 1).

Table 1. Mechanical properties of the materials.

Material	Young's modulus (MPa)	Poisson coefficient
Steel archwire	1.93×10^5	0.305
Steel brackets	1.93×10^5	0.305
Steel sphere	1.93×10^5	0.305

The materials used in this model have homogeneous elastic and isotropic properties, characterizing a linearly elastic model. Adequate forces were applied to the brackets into mesiodistal direction simulating the strength of the ligatures attaching the archwire into the bracket slot. The load of 0.5 N (2.5 g) was standardized to scale out the results and facilitate interpretation. In this analysis, it was considered the absence of difference in static and kinetic friction coefficient. A coefficient of friction (0.3) was estimated based on the Online Materials Information Resource (http://www.matweb.com). This value was inserted in the models as a constant, and its estimate was based on previous studies.[16] Only as a test of influence, if there was any type of lubrication, either by saliva or by the inclusion of a solid lubricant inside the bracket, the coefficient of friction was reduced to 0.1. For greater precision, these values are being validated and adjusted in further studies.

For reasons of simplification of the mathematical problem to be solved, a condition of symmetry with respect to the axial axis was imposed on the bracket models analyzed. Thus, in addition to reducing mesh complexity, the number of model interactions simulated through contact models was also reduced, which consequently reduced computational cost and facilitated the convergence of the model. Both interactions between the bracket in contact with the archwire for the conventional bracket and between the bracket in contact with the spheres and the spheres in contact with the archwire for the Roller Bracket were mathematically described with contact models composed of a normal "hard contact" behavior, where the normal reaction appears instantaneously when the nodes are approximated, and a tangential behavior simulating the Coulomb friction model using the Abaqus® model of penalties.

SIMULATION METHOD

Separate models of each of the involved parts were generated (archwire, conventional bracket and Roller Bracket). These models were analyzed, having as contour conditions the archwire and the load applied under the bracket relative to the effort generated by the ligature. Then, a displacement was imposed, simulating the traction exerted between two teeth where, given the implemented model of contact, the values of friction force could be followed. Through a contact analysis between the different models, it was intended to verify the variation of the friction force due to the bracket modification (insertion of spheres) and also to consider the lubrication coming from the saliva.

RESULTS

The mesh of the conventional bracket model consisted of a total of 1220 nodes, being 1053 nodes in the archwire representation and 167 in the bracket representation, in addition to 1099 elements (Figure 6). In turn, the mesh of the Roller Bracket model was constructed using a total of 4834 nodes, being 1053 nodes in the archwire representation, 3271 in the representation of the sliding sphere and 510 in the bracket representation, in addition to 4676 elements (Figures 7 and 8).

Figure 6. Conventional bracket model mesh with orthodontic wire.

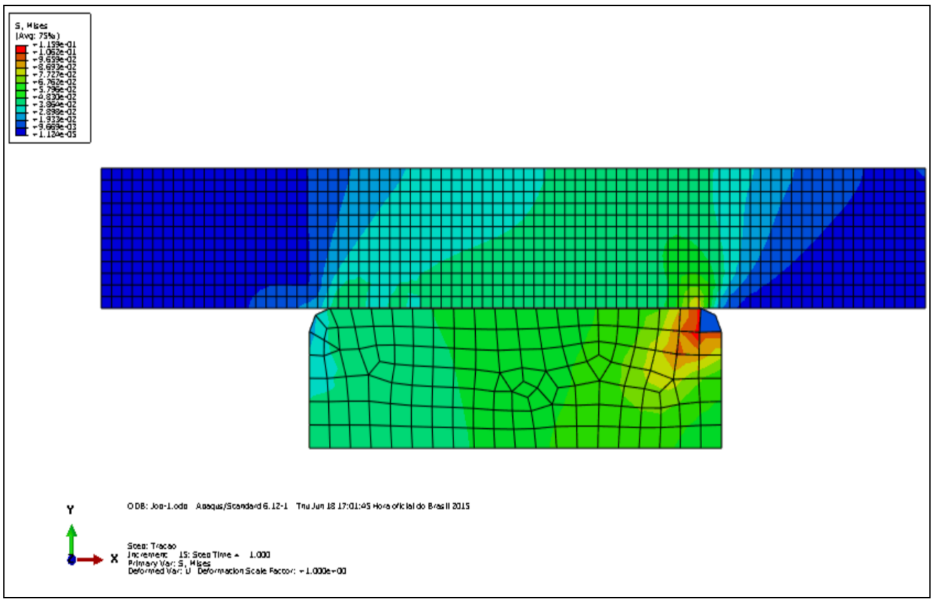


Figure 7. Roller Bracket model mesh associated with orthodontic wire without lubrication.

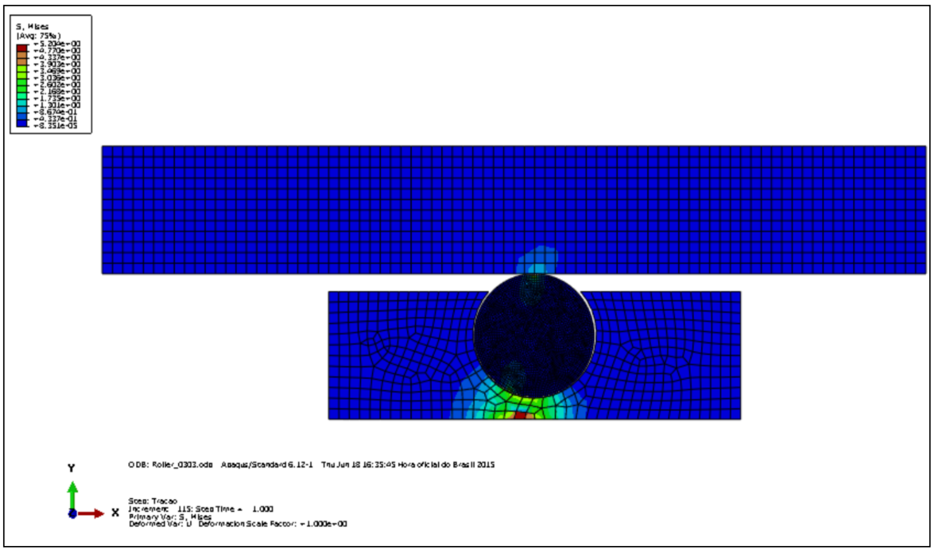
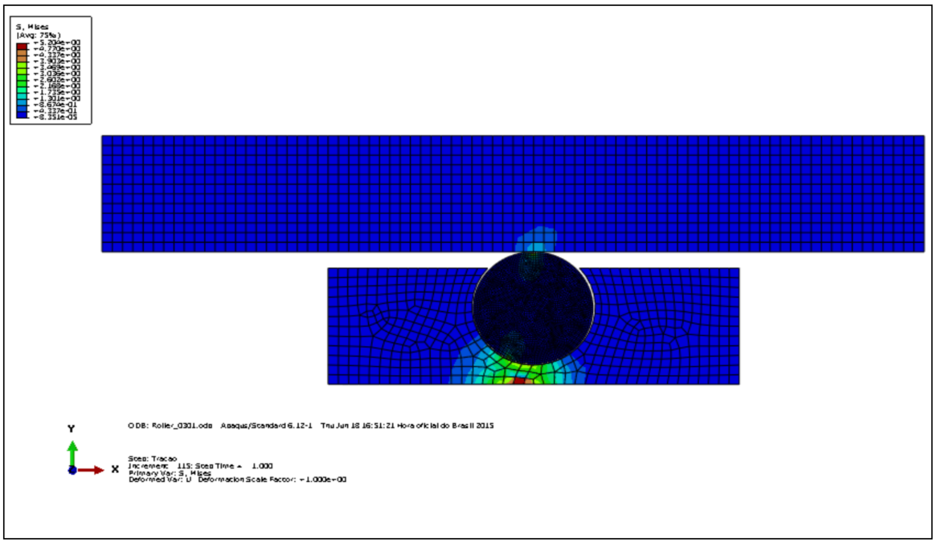


Figure 8 - Roller Bracket mesh model associated with orthodontic wire and considering lubrication



For each of the models, results were obtained with the displacements in the mesiodistal directions. From the beginning of the simulation, the models were considered in constant movement, with no static friction in the first moments, but rather with simulation instability. Therefore, it was preferred to rely on the values where the behavior was stable, until this model can be validated.

The oscillation observed at the beginning of the simulation can be attributed to mathematical instabilities and/or accommodations of the parts. Thus, the most reliable value of friction force was obtained when the simulation presented a stable load and behavior. In this way, considering the last steps of stabilization, the conventional bracket presented strength of 2.5 g, while the Roller Bracket presented strength of 2.2 g, meaning a reduction of 12% (Graph 1).

When the Roller Bracket test was performed considering the presence of a lubrication by the saliva or by a solid material (coefficient of friction = 0.1), the frictional force reached a value of 1.3 g (Graph 1), which represents a reduction of 41% in relation to the Roller Bracket without lubrication and 48% in relation to the conventional bracket. However, all cases still require validation, especially lubrication, since some studies have shown that saliva may have an opposite effect.[11]

DISCUSSION

The present study was conducted to compare the friction in both conventional and Roller Bracket by FEA. The results obtained in this work did not intend to quantify the frictional force but to describe it in qualitative terms. This mathematical model compares only the frictional force to its tendency to move. For this reason, the conclusion resulting from this research consists in indicating what would be occurring at the moment of the test, thus more mechanical tests are necessary to validate them. The main conclusion of this study is that, mechanically, the use of steel sliding spheres facilitated the energy dissipation, generating a lower friction between the archwire and the Roller Bracket when compared to the conventional bracket under the FEA model conditions.

It has been suggested that the friction between the bracket and the archwire is influenced by several factors, of which only a few are widely understood. In part, this is due to the fact that until recently there was no standardized method to accurately measure the frictional forces of materials used in orthodontics, either in a clinical or laboratory environment.[27,28] In this sense, *in vivo* and *in vitro* tests are considered the main approaches to study the resistance of friction between archwires and orthodontic brackets. However, some restrictive factors have been reported in relation to these approaches. For example, *in vivo* studies have as a limitation the fact that the coefficient of friction is strongly influenced by uncontrollable patient biological factors and, therefore, can produce unreliable results.[18] The present study was performed *in vitro* with FEA simulations under standardized conditions. In this method, there is a theoretical sub-division of the structure (discretization) while maintaining its continuity. The problem is solved for each element and then harmonized to achieve a representative system-wide response.[29] The main advantage of FEA method is that it can control any variable related to the experiment can be controlled, facilitating the analysis of the results and providing benefits to scientific research. In this sense, recent studies have shown the effectiveness of this method in orthodontics.[30,31] Although can be difficult to replicate these numerical data in clinical settings, useful information can be furnished to guide clinical research.[31]

Brackets, archwires and ligatures contribute to the friction generated during sliding mechanics. According to studies,[6,32] friction forces generally increase with the following variables: use of titanium-containing archwires, rectangular archwires, aesthetic brackets, increased archwire/bracket angulation, increased archwire cross-section, and increased fixation strength of the archwire in the bracket slot. In addition, some studies are controversial regarding the effects of intraoral lubricant simulation.

Low loads saliva can act as a lubricant.[33] On the other hand, high loads saliva may increase static friction if it is forced out from the contact surfaces between the brackets and the archwire, producing shear resistance sliding forces.[33] Other studies found no changes in the coefficient of friction in different orthodontic materials, comparing dry or non-dry conditions.[6,18] In the present study, the results indicated a significantly higher friction in the conventional bracket compared to the Roller Bracket under dry conditions. In addition, tests considering the same coefficient of friction and time of displacement of the bracket for both models showed a significant reduction in the friction between the archwire and the spheres after the insertion of lubrication, such as saliva. These values can be validated and adjusted. Thus, in the present study, saliva acted as a coadjuvant factor in the reduction of friction.

Some authors have pointed out that stainless steel bracket and archwire sets have a lower coefficient of friction during sliding mechanics when compared to other combinations of materials.[3,6,9] Other study detected no significant differences between the resistance to sliding concerning nickel titanium and stainless steel archwires.[32] According to Articolo and Kusy,[3] less friction between appliances made of the same materials occurs in passive configuration. The present study was carried out considering stainless steel archwires with rectangular cross-section and appropriate magnitude of force during orthodontic movement. Therefore, the present results showed that, in FEA model, the addition of steel sliding spheres promoted even lower friction than stainless steel conventional brackets and archwires.

In general, studies showed that aesthetic brackets may produce more friction during sliding mechanics than stainless steel brackets.[9,33-35] A study[35] have pointed out that the friction remains independent of the material of the aesthetic bracket slot while other[37] stated that it occurs in both .018 " and .022" slot size. These authors attributed the differences of friction between the conventional and aesthetic brackets to the surface texture characteristics that each material presents. The present study compared the coefficient of friction between the conventional bracket and Roller Bracket, both made of stainless steel and with slot size .022" x .030" and found that the Bracket Roller presented lower friction. Further research is underway to confirm whether aesthetic Roller Bracket will also present a lower coefficient of friction when compared to conventional aesthetic brackets due to the incorporation of sliding spheres in its structural characteristic.

The difference in friction generated between conventional and self-ligating brackets remains subject of several discussions in the scientific community. Vartolomei et al[37] reported a decrease of friction in self-ligating brackets when compared to conventional brackets. On the other hand, systematic reviews have pointed out that there is not enough scientific basis to determine the superiority of the self-ligating brackets in relation to treatment efficiency.[23,24] Studies evaluating friction during sliding mechanics comparing self-ligating Roller Bracket and self-ligating brackets are still in progress, including employing different archwire types. Therefore, these analyzes can provide useful results to clarify these aspects.

The present study provides initial evidence regarding the reduction of friction due to the insertion of sliding spheres in the Roller Bracket. However, the methodology used has limitations like any mathematical model. Some factors related to FE method may lead to inaccurate results, such as the simplifications necessary for the adoption of a given mathematical model and the division of complex structures into various geometric forms that can result in loss of details.[38] In addition, the data obtained in this study did not consider the complexity of the oral environment. Authors have shown that changes in inter-bracket distance and in biological factors such as temperature, humidity and salivary acidity can lead to variations in friction values.[18,39] Although these changes are not amenable to laboratory simulation, comparative data from such tests are potentially useful for guiding research related to new orthodontic appliances such as Roller Bracket, which can minimize the force used in the sliding mechanics, as well as to reduce the treatment time, resulting in biological benefits for the patient.

CONCLUSION

The use of steel sliding spheres in the Roller Bracket facilitated the energy dissipation, generating a lower friction when compared to the conventional bracket when using a .022" x .030" SS archwire.

AUTHOR CONTRIBUTION

L.S.M, M.L.R.J participated in conception and design of the work, analyzed and interpreted data of the work, critically revised the manuscript, approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

P.A.M.J, C.C.P.F participated in data acquisition, analysis, interpretation of data, drafted the manuscript, approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

CONFLICT OF INTEREST

The Roller Bracket was patented by the first author. It was registered at the National Institute of Industrial Property (INPI) under the number 1101640.

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REFERENCES

1. Tecco S, Di Iorio D, Nucera R, Di Bisceglie B, Cordasco G, Festa F. Evaluation of the friction of self-ligating and conventional bracket systems. Eur J Dent. 2011;5(3):310-7.
2. Araújo RC, Bichara LM, Araujo AM, Normando D. Debris and friction of self-ligating and conventional orthodontic brackets after clinical use. Angle Orthod. 2015;85(4):673-7.
3. Articolo LC, Kusy RP. Influence of angulation on the resistance to sliding in fixed appliances. Am J Orthod Dentofacial Orthop. 1999;115:39-51.
4. Harris DA, Jones AS, Darendeliler MA. Physical properties of root cementum: part 8. Volumetric analysis of root resorption craters after application of controlled intrusive light and heavy orthodontic forces: a microcomputed tomography scan study. Am J Orthod Dentofacial Orthop. 2006;130(5):639-47.
5. Harry MR, Sims MR. Root resorption in bicuspid intrusion: a scanning electron microscope study. Angle Orthod. 1982;52(3):235-58.
6. Kusy RP, Whitley JQ. Friction between different wire-bracket configurations and materials. Semin Orthod. 1997;3(3):166-77.
7. Burrow SJ. Friction and resistance to sliding in orthodontics: a critical review. Am J Orthod Dentofacial Orthop. 2009;135(4):442-7.
8. Kusy RP, Whitley JQ. Influence of archwire and bracket dimensions on sliding mechanics: derivations and determinations of the critical contact angles for binding. Eur J Orthod. 1999;21(2):199-208.
9. Arici N, Akdeniz BS, Arici S. Comparison of the frictional characteristics of aesthetic orthodontic brackets measured using a modified in vitro technique. Korean J Orthod. 2015;45(1):29-37.
10. Monteiro MRG, Silva LE, Elias CN, Vilella OV. Frictional resistance of self-ligating versus conventional brackets in different bracket-archwire-angle combinations. J Appl Oral Sci. 2014;22(3):228-34.
11. Meier MJ, Bourauel C, Roehlike J, Reimann S, Keilig L, Braumann B. Friction behavior and other material properties of nickel-titanium and titanium-molybdenum archwires following electrochemical surface refinement. J Orofac Orthop. 2014;75:308-19.
12. Tecco S, Tetè S, Festa F. Friction between archwires of different sizes, cross-section and alloy and brackets ligated with low-friction or conventional ligatures. Angle Orthod. 2009;79(1):111-6.
13. Kumar S, Singh S, Hamsa PRR, Ahmed S, Prasanthma, Bhatnagar A, et al. Evaluation of friction in orthodontics using various brackets and archwire combinations-an in vitro study. J Clin Diagn Res. 2014;8(5):ZC33-6.
14. Choi S, Kang D, Hwang C. Surface roughness of three types of modern plastic bracket slot floors and frictional resistance. Angle Orthod. 2014;84(1):177-83.
15. Alfonso MV, Espinar E, Llamas JM, Rupérez E, Manero JM, Barrera JM, et al. Friction coefficients and wear rates of different orthodontic archwires in artificial saliva. J Mater Sci Mater Med. 2013;24:1327-32.
16. Cacciafesta V, Sfondrini MF, Ricciardi A, Scribante A, Klersy C, Auricchio F. Evaluation of friction of stainless steel and esthetic self-ligating brackets in various bracket-archwire combinations. Am J Orthod Dentofacial Orthop. 2003;124(4):395-402.
17. Zufall SW, Kennedy KC, Kusy RP. Frictional characteristics of composite orthodontic archwires against stainless steel and ceramic brackets in the passive and active configurations. J Mater Sci Mater Med. 1998;9:611-20.
18. Stannard JG, Gau JM, Hanna MA. Comparative friction of orthodontic wires under dry and wet conditions. Am J Orthod. 1986;89(6):485-91.
19. Kachoei M, Nourian A, Divband B, Kachoei Z, Shirazi S. Zinc-oxide nanocoating for improvement of the antibacterial and frictional behavior of nickel-titanium alloy. Nanomedicine (Lond). 2016;11:2511-27.
20. Redlich M, Mayer Y, Harari D, Lewinstein I. In vitro study of frictional forces during sliding mechanics of “reduced-friction” brackets. Am J Orthod Dentofacial Orthop. 2003;124(1):69-73.
21. Cunha AC, Marquezan M, Freitas AOA, Nojima LI. Frictional resistance of orthodontic wires tied with 3 types of elastomeric ligatures. Braz Oral Res. 2011;25(6):526-30.
22. Castro RM, Smith Neto P, Horta MCR,

10.35699/2178-1990.2024.51019

Pithon MM, Oliveira DD. Comparison of static friction with self-ligating, modified slot design and conventional brackets. J Appl Oral Sci. 2013;21(4):314-9.
23. Ehsani S, Mandich M, El-Bialy TH, Flores-Mir C. Frictional resistance in self-ligating orthodontic brackets and conventionally ligated brackets: a systematic review. Angle Orthod. 2009;79(3):592-601.
24. Čelar AG, Schedlberger M, Dörfler P, Bertl MH. Systematic review on self-ligating vs. conventional brackets: initial pain, number of visits, treatment time. J Orofac Orthop. 2013;74:40-51.
25. Angolkar PV, Kapila S, Duncanson Jr MG, Nanda RS. Evaluation of friction between ceramic brackets and orthodontic wires of four alloys. Am J Orthod Dentofacial Orthop. 1990;98(6):499-506.
26. Kapila S, Angolkar PV, Duncanson Jr MG, Nanda RS. Evaluation of friction between edgewise stainless steel brackets and orthodontic wires of four alloys. Am J Orthod Dentofacial Orthop. 1990;98(2):117-26.
27. Fathimani M, Melenka GW, Romanyk DL, Toogood RW, Heo G, Carey JP, et al. Development of a standardized testing system for orthodontic sliding mechanics. Prog Orthod. 2015;16:14.
28. Mencattelli M, Donati E, Cultrone M, Stefanini C. Novel universal system for 3-dimensional orthodontic force-moment measurements and its clinical use. Am J Orthod Dentofacial Orthop. 2015;148(1):174-83.
29. Geramy A. Initial stress produced in the periodontal membrane by orthodontic loads in the presence of varying loss of alveolar bone: a three-dimensional finite element analysis. Eur J Orthod. 2002;24(1):21-33.
30. Aykaç V, Ulusoy Ç, Türköz Ç. Effects of a newly designed orthodontic miniplate platform for elevating the miniplate over the gingiva: a 3-dimensional finite element analysis. Am J Orthod Dentofacial Orthop. 2015;148(1):110-22.
31. Papageorgiou SN, Keilig L, Hasan I, Jäger A, Bourauel C. Effect of material variation on the biomechanical behaviour of orthodontic fixed appliances: a finite element analysis. Eur J Orthod. 2016;38(3):300-7.
32. Loftus BP, Ârtun J, Nicholls JI, Alonzo TA, Stoner JA. Evaluation of friction during sliding tooth movement in various bracket-arch wire combinations. Am J Orthod Dentofacial Orthop. 1999;116(3):336-45.
33. Pratten DH, Popli K, Germane N, Gunsolley JC. Frictional resistance of ceramic and stainless steel orthodontic brackets. Am J Orthod Dentofacial Orthop. 1990;98(5):398-403.
34. Bednar JR, Gruendeman GW, Sandrik JL. A comparative study of frictional forces between orthodontic brackets and arch wires. Am J Orthod Dentofacial Orthop. 1991;100(6):513-22.
35. Thorstenson GA, Kusy RP. Comparison of resistance to sliding between different self-ligating brackets with second-order angulation in the dry and saliva states. Am J Orthod Dentofacial Orthop. 2002;121(5):472-82.
36. Drescher D, Bourauel C, Schumacher HA. Optimization of arch guided tooth movement by the use of uprighting springs. Eur J Orthod. 1990;12(3):346-53.
37. Vartolomei A, Serbanoiu D, Ghiga D, Moldovan M, Cuc S, Pollmann MCF, et al. Comparative evaluation of two bracket systems' kinetic friction: conventional and self-ligating. Materials (Basel). 2022;15(12):4304.
38. Sameshima GT, Melnick M. Finite element-based cephalometric analysis. Angle Orthod. 1994;64(5):343-50.
39. Chang C, Lee T, Liu J. Effect of bracket bevel design and oral environmental factors on frictional resistance. Angle Orthod. 2013;83:956-65.