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Gameiro, GH;Bocchiardo, JE;Dalstra, M;Cattaneo, PM

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Individualization of the three-piece base arch mechanics according to various periodontal support levels: A finite element analysis

Running title: Mechanics for periodontally compromised dentitions

Gustavo Hauber Gameiro,[a] Jorge Eugenio Bocchiardo,[b] Michel Dalstra,[c,d] Paolo Maria Cattaneo[c]

[a]Associate Professor of Physiology, Department of Physiology, Federal University of Rio Grande do Sul – UFRGS, Porto Alegre, Brazil.

[b]Aeronautical Engineer, Postgraduate in Data Analytics, Universitat de Barcelona, Barcelona, Spain.

[c]Associate professor, Section of Orthodontics, Department of Dentistry and Oral Health, Faculty of Health Science, Aarhus University, Aarhus, Denmark.

[d]Associate professor, Department of Pediatric Oral Health and Orthodontics, University Center for Dental Medicine Basel (UZB), University of Basel, Basel, Switzerland.

Corresponding Author:

Paolo M. Cattaneo, Section of Orthodontics, Department of Dentistry and Oral Health, Aarhus University, Vennelyst Boulevard 9, DK-8000 Aarhus C, Denmark

E-mail: paolo.cattaneo@dent.au.dk

Telephone +45 87167459

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ABSTRACT

Introduction: The orthodontic correction of periodontally compromised dentitions constitutes a huge challenge in the clinical practice of adult orthodontics. The biological and physical distinct features of these conditions require a carefully designed mechanical plan for the successful treatment of these complex cases. **Setting and Sample Population:** A segment of a human maxilla containing the central and lateral incisors, obtained from autopsy, was scanned with microcomputed tomography, and a finite element (FE) model was generated to represent an intact periodontal dentition. Based on this model, three additional models simulating a mild, moderate, and severe bone alveolar loss were created as well. **Materials and Methods:** Two loading scenarios for the application of intrusive and retraction mechanics with a three-piece base arch appliance were evaluated in a series of FE analyses. The tooth displacements and strains in the periodontal ligament (PDL) were calculated and compared for the four FE models. **Results:** The periodontal reduced dentitions exhibited a similar axis of resistance for intrusive mechanics, but the axis of resistance for retraction movements was significantly dependent on the degree of alveolar bone loss. The tooth displacements and PDL loads were higher in the reduced dentitions for both intrusive and retraction mechanics. **Conclusions:** A reduction in the force levels applied to periodontal reduced dentitions is indicated, and a customized selection of appropriate points of force application is needed according to the specific amount of alveolar bone loss.

Keywords: Finite Element Analysis, Periodontal Ligament, Tooth Movement Techniques

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DR GUSTAVO HAUBER GAMEIRO (Orcid ID : 0000-0003-4365-6643)

DR PAOLO CATTANEO (Orcid ID : 0000-0001-7604-3259)

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INTRODUCTION

The main occlusal changes observed in patients with periodontal problems include proclination of the maxillary anterior teeth, rotations, overeruption, migration, tooth loss, irregular interdental spacing, and traumatic occlusion.[1-3] Because of their considerable negative impact on patients' self-esteem, these malocclusions are often why adult patients to seek periodontal and orthodontic therapy.[4,5] Periodontal diseases contribute to the development of malocclusions in different ways. With the loss of alveolar bone caused by periodontitis, the center of resistance (CR) of teeth is displaced apically, whereby the occlusal forces on the incisors can lead to unfavorable tipping and extrusion of these teeth.[6,7]

The intrusion and retraction of the maxillary incisors has been applied as the logical solution to the orthodontic problems of these patients when considered from causative, esthetic, and functional points of view. There are several mechanics for the intrusion of anterior teeth, such as utility arches or round wires with tip-back bends that are mesial to molars,[8,9] continuous intrusion arches,[10] and conventional continuous archwires with or without the addition of extraoral forces.[11,12] All of these treatment approaches have merit and can be applied for the intrusion of teeth that have normal bone support. However, they are not indicated when dealing with periodontally compromised dentitions.[13,14] For example, in clinical situations where the incisors are flared and the bone support is reduced, the application of an intrusive force on the brackets would exacerbate the axial inclination of these teeth.[15] Moreover, the forces applied to a reduced periodontium generate significantly higher strains in the periodontal ligament (PDL), which can be detrimental for both the bone and the tooth by increasing the risks of bone loss and root resorption, respectively.[13,16] Therefore, in these cases, the appropriate control of both the direction and magnitude of the force by means of a customized mechanical plan is highly recommended.

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Among others, one versatile appliance for performing the intrusion and retraction of anterior teeth with reduced periodontium is the three-piece intrusion base arch.[15,17] This appliance consists of an anterior rigid segment of wire that extends distally to the lateral incisors and two bilateral tip-back springs or cantilevers that extend from the auxiliary tube of the molar and hook anteriorly at the estimated CR position of the anterior group of teeth. The tip-back springs or cantilevers are usually made from 0.017” x 0.025” titanium molybdenum alloy and deliver a nearly constant force. The magnitude of force indicated for the four intruding maxillary incisors is typically 30–40 g per side.[13,15,17] Additional distal forces from the molars can be applied to redirect the forces along the long axis of the incisors or to perform simultaneous retraction, according to the needs of each case. To apply a predictable and desirable force system for intrusion and/or retraction, an estimation of the anterior teeth CR is mandatory, which constitutes a clinical challenge when using this type of mechanism. Although it is well known that the CR of the anterior teeth is displaced when there is reduced periodontal support,[6,13,18] its precise localization depends on the actual extent of the alveolar bone loss. To our knowledge, there are no precise guidelines available to help select the points of application of the intrusive and retraction forces in periodontally damaged dentitions when taking into consideration various degrees of alveolar bone loss.

Therefore, the present finite element (FE) study was designed to evaluate the mechanical behavior of periodontally compromised dentitions submitted to customized mechanics with the three-piece intrusion base arch appliance. The specific aims of the study were:

- To evaluate the tooth displacements and strain profiles in the PDL of dentitions with different degrees of alveolar bone loss.

- To estimate the localization of the center of resistance of anterior teeth for both intrusive and retraction mechanics, according to the different periodontal models.

- To evaluate the effects of reduced load regimens on the PDL of the four models in the “ideal” intrusive and retraction scenarios.

MATERIALS AND METHODS

A segment of an anterior maxilla, including the central and lateral incisors, was obtained during an autopsy (approval obtained from the Regional Ethics Committee JrNr 20010016) and was scanned with a micro-CT (µCT) scanner with a voxel dimension of 37 µm (µCT40, Scanco Medical, Bassersdorf, Switzerland). Image processing software (Mimics 16, Materialise, Leuven, Belgium) was used to generate a 3D model of the upper anterior dentition with normal bone support, with an approximate distance of 1 mm between the cemento–enamel junction and the alveolar bone crest (Figure 1, step 1). As the original model did not comprise the right lateral incisor, the final model was created by mirroring the left part of the scan using the intermaxillary suture as the mirroring plane. From this model of intact periodontal dentition, three additional unilateral models were created to

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represent mild, moderate, and severe bone loss by removing 2, 4, or 6 mm of alveolar bone, respectively.[19] The PDL tissue was modeled as the space between the alveolar sockets and roots of the teeth. The three-piece intrusion arch appliance was modeled to simulate a clinical scenario in which all possible points of force application could be tested, regarding both intrusion and retraction mechanics. With the use of meshing generator software (3-Matic 7.10, Materialise, Leuven, Belgium), the different anatomical parts of the dentition, the brackets, and the appliance were meshed using ten-node tetrahedral elements (Figure 1, step 2). The intact model was composed of 69,175 elements and 12,586 nodes. The mild model was composed of 166,875 elements and 27,948 nodes. The moderate model was composed of 136,095 elements and 24,906 nodes, and the severe model was composed of 60,786 elements and 11,323 nodes. All models were imported into the finite element software FEMAP 10.0 (Siemens PLM Software Inc., Santa Ana, CA, USA) for load application and to carry out tooth displacement and PDL strain evaluation and analysis.

The material properties of the teeth, the brackets, and the anterior segment of the wire were assigned according to the available literature.[6,13,20] The Young's modulus for teeth was 20,000 MPa with a Poisson's ratio of 0.3.[21] The brackets and wire were assumed to be steel, with a Young's modulus of 200,000 MPa and a Poisson's ratio of 0.3. The properties of bone were assigned to each element individually based on the element's centroid and the corresponding bone type and morphology, as retrieved from the µCT scan; a greyscale was then applied to the Young's modulus conversion according to a procedure previously described by Cattaneo et al.[22] Briefly, three Young's moduli were considered for the analysis: full cortical bone (17,500 MPa, Poisson's ratio of 0.3), partly cortical bone (5000 MPa, Poisson's ratio of 0.3), and bone marrow (200 MPa, Poisson's ratio of 0.3). A nonlinear and nonsymmetric approach was used to describe the material properties of the PDL in which the compression and tension properties are not the same.[23] In compression, a Young's modulus of 0.005 MPa up to the 93% strain level was used,[24] and a Young's modulus of 8.5 MPa was then adopted to simulate precontact between the roots and the alveolar bone. Regarding tension, the Young's moduli were gradually increased from 0.044 MPa at zero strain to 0.44 MPa at approximately 50% strain,[25] then a smaller Young's modulus of 0.032 MPa was applied. A Poisson's ratio of 0.3 was used for the PDL.[23,26]

To represent all possible mechanical scenarios with the three-piece intrusion base arch appliance, the load regimes and results were analyzed from two different perspectives. First, for intrusion evaluation, vertical loads were applied from 1 to 10 mm away from the lateral incisor bracket in the horizontal arm of the appliance (Figure 2A). In this perspective, both a normal load (40 g/side, as indicated by previous studies) and a reduced load regime were applied (–25% = 30 g/side). Second, for retraction evaluation, horizontal loads were applied from 1 to 10 mm away from the lateral incisor bracket in the vertical arm of the appliance (Figure 2B). Again, both a normal load (100 g/side, indicated by previous studies) and a reduced load regime were applied (–20% = 80 g/side). Considering the nonlinear feature of the present analysis, the loads were applied in an incremental fashion until the desired load

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level was reached. For the boundary conditions, the bottom edge of the maxilla segments was fixed in all three directions.

The tooth displacements and CR estimations were evaluated by two methods—a graphical method and a numerical method. In the graphical method, color coding was used to visualize the displacements of the elements in specific directions using the occlusal plan as the reference for the coordinate system (X-axis = mesiodistal direction; Y-axis = anteroposterior direction; and Z-axis = vertical direction). In the present study, only intrusion (along the Z-axis) and retraction (along the Y-axis) components were evaluated. The elements' displacements were represented by color progression from blue (lowest value) to red (highest value). In this way, we could observe when most of the elements of the teeth were moving with the same intensity in each specific direction. By comparing the different load scenarios for each movement (Figure 2), the point of force application in which a maximum number of elements had the same color was considered the "ideal" point for a genuine intrusion or a pure retraction.

The numerical method was applied to confirm the graphically observed results. Two nodes on each tooth were chosen (one in the incisal edge and the other at the apex), and the displacements of these nodes were computed for both intrusion and retraction mechanics. To estimate the CR zone for intrusion, the differences of the vertical displacements between the apex and incisal edge nodes were compared. The lowest displacement value indicated the point of force application in which the movement was closest to a clinical translation in the vertical direction (Z-axis). Similarly, to estimate the CR zone for retraction, the differences in the horizontal displacements between the apex and incisal edge nodes were compared. The lowest displacement value indicated the point of force application in which the movement was closest to a clinical translation in the anteroposterior direction (Y-axis). The term "zone of the CR" was applied in the present study in accordance with recent evidence showing that the CR can be constructed in 3D space not as a point, but as a small 3D volume.[27,28]

For both intrusion and retraction movements, the PDL strains induced by these mechanics were assessed with respect to the generated radial strains in the periodontal ligament. The PDL strains were evaluated both graphically and numerically, according to the application of the "ideal mechanics" for each model, in both load regimens (normal and reduced forces), and for both intrusion and retraction mechanics.

RESULTS

The numerical tooth displacement results used for the CR estimation for the intrusion and retraction load regimens are reported in Tables 1 and 2, respectively. For intrusion, in the four models evaluated, the ideal point for a vertical translation was V6 – a point localized 6 mm away from the bracket of the lateral incisor in the horizontal arm of the appliance. The graphic results were

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consistent with the numerical results and are shown in Figure 3. Taken together, these results indicate that the clinical CR zone for intrusive movements did not change with respect to the degree of bone loss (Table 1, Figure 3).

By contrast, in relation to the load regime of the retraction mechanics, the numerical tooth displacement results demonstrated that the ideal point of force application to obtain a horizontal bodily movement is significantly dependent on the height of available bone support. In the normal model, this point was localized 6 mm away from the bracket of lateral incisor in the vertical arm of the appliance (D6). In the mild, moderate, and severe models, these ideal points were D8, D9, and D10, respectively (Table 2). The pure translation obtained when forces were applied at these specific points is also shown in Figure 3. Therefore, the CR zone for retraction movements significantly varies depending on the severity of alveolar bone loss. As the amount of bone loss increases, the position of the CR zone for a pure retraction becomes higher (i.e., more apical).

The effects of the force magnitudes on PDL strains induced by intrusive mechanics were compared and are shown in Figure 4. The minimum (compression, in blue) and maximum (tension, in red) radial strain values varied according to the severity of bone loss, especially the compressive strain in the PDL of the lateral incisor. In general, the higher the degree of bone loss, the larger the compressive strain. When the force magnitude was reduced by 25%, small reductions (approximately 5–10%) in both the compressive and tensile strains were observed, mainly in the compressive strain in the lateral incisor.

The retraction mechanics showed a similar pattern to that observed for the intrusive mechanics. However, the PDL strains were generally higher than those induced by the intrusion set-up. Even the normal and mild–moderate bone loss models presented compressive strains greater than 20%, but the highest strains were observed in the moderate and severe models, mainly in the lateral incisors. The reduced load regime (–20%) induced a small reduction (approximately 5%) in the PDL strains of the four evaluated FE models (Figure 4).

DISCUSSION

The present FEM study evaluated the most important biomechanical parameters in the scenario of intrusion and retraction mechanics using a three-piece base arch appliance. This appliance has broad versatility owing to the many points of possible force application along both its horizontal and vertical arms with different lines of action. Moreover, the combination of intrusive and retraction forces can be used to increase the predictability and accuracy of the force system when applied to each particular case.[15,17] The main clinical indications for this appliance are those in which the incisors are flared and

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extruded, such as in pathological tooth migration, a condition with a very high prevalence among periodontal patients, ranging from 30% to 56%.[4] The main cause of this problem is the periodontal inflammation and tissue destruction associated with chronic periodontitis in which the severity of bone loss is classified as mild, moderate, or severe/advanced.[14,19] After periodontal inflammation is brought under control through proper periodontal therapy, the orthodontic correction of the malpositioned teeth will improve the function and esthetics of the dentition.[14] However, the level of complexity for treating these cases will largely depend on the severity of the alveolar bone loss.[6,13,18,29]

Several finite element studies have been conducted to analyze the patterns of tooth displacements associated with different amounts of alveolar bone support.[6,13,18,29-32] In general, the tooth displacements, induced by several types of mechanics, are always greater in models with reduced bone support. Most of the related studies have tested the application of simple force systems in single tooth models.[6,18,29-32] Furthermore, all of the previous FE studies used homogeneous, linear elastic, isotropic, and continuous material properties to describe the PDL, with the exception of one study in which a patient-customized 3D model of a periodontally reduced dentition with different PDL parameters was assessed.[13] In that study, two mechanical scenarios for intrusion were investigated—the first using the three-piece base arch appliance, and the second using cantilevers for single tooth intrusion. The study demonstrated that both intrusion systems involved significantly greater degrees of tooth displacement and PDL strain in the periodontally reduced model.[13] These results, obtained in a single patient-customized model, are in accordance with those of the present investigation in which different, specific alveolar bone loss conditions were evaluated to obtain a more complete view of the clinical scenario when a three-piece base arch appliance is used.

The present results show that successful clinical planning for these complex cases depends on the application of a predictable force system that allows moving the anterior teeth in the desired direction. In clinical settings, the accurate determination of the point of force application for both intrusion and retraction movements requires a reliable estimation of the anterior teeth CR zone. Our results demonstrated that the clinically “ideal” point to obtain a genuine intrusion of the anterior teeth using a three-piece base arch appliance was localized 6 mm away from the bracket of the lateral incisor, in the horizontal arm of the appliance (point V6). This ideal localization was the same in all evaluated models (Table 1 and Figure 3), regardless of the degree of alveolar bone loss.

The load regime for retraction mechanics exhibited a different scenario. To obtain a horizontal translation of the anterior teeth, the points of force application were different for each simulated bone support level. In the intact periodontal model, the “ideal” point was localized 6 mm away from the bracket of the lateral incisor, in the vertical arm of the appliance (point D6). When the retraction force was applied at this point, a retraction similar to a pure horizontal translation was seen. This conclusion was based on both the numerical calculations (Table 2) and the graphical observations (Figure 3). By contrast, the “ideal” points for translation in the periodontally reduced models were D8, D9, and D10 for the mild, moderate, and severe bone loss conditions, respectively. These results indicate that the

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CR axis of anterior teeth for horizontal translation is heavily dependent on the amount of alveolar bone loss. The greater the bone loss, the higher (more apical) the estimated location of the CR axis for retraction movement. Periodontal damage and the associated alveolar bone loss occur on both the buccal and lingual sides of dentitions. Therefore, the axis of resistance for intrusion did not change in the same way as the axis of resistance for retraction did, because the latter is influenced by the bone loss that occurs mainly in the cervical to apical direction, as simulated in the present investigation.
The second aim of this study was to compare the radial strains induced in the PDL of the moved teeth. Although it is possible to look at several variables in FE simulations, this investigation focused on radial PDL strains. The stress/strain fields in the PDL were indeed proved to have the most significant correlations with the biological responses of bone and root resorption.[33-36] Not surprisingly, the results of the present FE analyses showed that the PDL strains induced in the periodontally reduced models were generally higher than the PDL strains induced in the intact normal model. When simulating the intrusive loading scenario, the PDL deformation increased by approximately 10% to 40% when the periodontally reduced models were evaluated (Figure 4). These differences were not as significant in the retraction loading scenario. The retraction forces applied at the ideal points identified by each FE model induced similar PDL strains in the normal and mild bone loss models. However, higher strain components in the retraction loading scenario were observed in the PDL of the lateral incisors in the moderate and severe FE models (Figure 4). A reduced force generated lower PDL strains in all models in both the intrusive and retraction loading scenarios. The reduction in PDL strain was more evident in the intrusive scenario, with approximately 10% reductions of the compressive and tensile strains. It is important to point out that not only the maximum and/or minimum values had changed but also the amount of area in the PDL experiencing high strain values. Considering that the compressive strains are usually more dangerous for the support tissues than the tensile strains are,[33-36] the reduction in the compressed area (blue area) in the periodontally compromised models is a clear indication that the intrusive forces should be reduced in these conditions (Figure 4). The force reduction indicated by the present analysis (–20 to –25%) is similar to the reduction suggested by a previous FE study of intrusion in a periodontally damaged dentition (–30%).[13]
When evaluating the force reduction effects during the retraction scenario, we observed a small reduction in the PDL strains (approximately 5%) in the evaluated FE models. This reduction was more evident in the PDL of the lateral incisors. Considering that all models had high PDL strains, with values of approximately 20% or higher, it is advisable to reduce the force levels in all models. Although there is no known safe “strain threshold” for the PDL, the literature clearly indicates that values above 20% would result in a higher risk of root resorption.[13,33-35] Therefore, these risks should be always minimized, especially in periodontally compromised dentitions in which the root support is already reduced by the alveolar bone loss.

This study used FE models based on actual morphologies of bone and teeth. The physical properties of the PDL and the surrounding bone were set according to physiological parameters in order to closely simulate a real clinical situation. However, some limitations of this study should be mentioned.

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The analyses were based on only one human sample, thus with specific tooth dimensions, inclinations, and root anatomy. Therefore, we cannot extrapolate these scenarios to all clinical conditions involving alveolar bone loss. Moreover, only the first phase of tooth movement could be assessed. Despite these limitations, the present FE study provides us with useful numerical approximations that can be used as clinical guidelines when dealing with different levels of periodontally damaged dentitions.

CONCLUSIONS

- Numerical simulations for estimating the CR axis of vertical and horizontal translations using a three-piece base arch appliance were established according to specific amounts of alveolar bone loss. The alveolar bone height did not affect the vertical CR axis, but it did affect the localization of the horizontal CR axis. The greater the amount of bone loss, the higher (more apical) the ideal point of force application to obtain a retraction bodily movement of the anterior teeth.

- The tooth displacements and PDL strains induced by the intrusive and retraction mechanics were larger in the reduced periodontal dentitions; thus, a 20% to 25% reduction in the applied load is highly recommended when using this type of mechanics.

- Useful guidelines for optimizing the use of three-piece base arch mechanics in clinical practice are presented, with an emphasis on the choice of the most appropriate point of force application according to specific amounts of alveolar bone loss.

REFERENCES

1. Ong MA, Wang HL, Smith FN. Interrelationship between periodontics and adult orthodontics. *J Clin Periodontol.* 1998;25(4):271-277.
2. Fukunaga T, Kuroda S, Kurosaka H, Takano-Yamamoto T. Skeletal anchorage for orthodontic correction of maxillary protrusion with adult periodontitis. *Angle Orthod.* 2006;76(1):148-155.
3. Gkantidis N, Christou P, Topouzelis N. The orthodontic-periodontic interrelationship in integrated treatment challenges: a systematic review. *J Oral Rehabil.* 2010;37(5):377-390.
4. Brunsvold MA. Pathologic tooth migration. *J Periodontol.* 2005;76(6):859-866.
5. McKiernan EX, McKiernan F, Jones ML. Psychological profiles and motives of adults seeking orthodontic treatment. *The International journal of adult orthodontics and orthognathic surgery.* 1992;7(3):187-198.

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6. Tanne K, Nagataki T, Inoue Y, Sakuda M, Burstone CJ. Patterns of initial tooth displacements associated with various root lengths and alveolar bone heights. Am J Orthod Dentofacial Orthop. 1991;100(1):66-71.
7. Melsen B. *Adult orthodontics.* Chichester: Wiley-Blackwell; 2012.
8. Mulligan TF. The advantages of differential moments. *J Clin Orthod.* 2009;43(6):379-386.
9. Ricketts RM. The wisdom of the bioprogressive philosophy. *Semin Orthod.* 1998;4(4):201-209.
10. Burstone CR. Deep overbite correction by intrusion. *Am J Orthod.* 1977;72(1):1-22.
11. Horiuchi Y, Horiuchi M, Soma K. Treatment of severe Class II Division 1 deep overbite malocclusion without extractions in an adult. *Am J Orthod Dentofacial Orthop.* 2008;133(4 Suppl):S121-129.
12. Paik CH, Park HS, Ahn HW. Treatment of vertical maxillary excess without open bite in a skeletal Class II hyperdivergent patient. *Angle Orthod.* 2017;87(4):625-633.
13. Kettenbeil A, Reimann S, Reichert C, Keilig L, Jager A, Bourauel C. Numerical simulation and biomechanical analysis of an orthodontically treated periodontally damaged dentition. *Journal of orofacial orthopedics.* 2013;74(6):480-493.
14. Cardaropoli D, Gaveglio L, Abou-Arraj RV. Orthodontic movement and periodontal bone defects: Rationale, timing, and clinical implications. *Semin Orthod.* 2014; 20(3):177-187.
15. Shroff B, Yoon WM, Lindauer SJ, Burstone CJ. Simultaneous intrusion and retraction using a three-piece base arch. *Angle Orthod.* 1997;67(6):455-461; discussion 462.
16. Melsen B, Agerbaek N, Markenstam G. Intrusion of incisors in adult patients with marginal bone loss. *Am J Orthod Dentofacial Orthop.* 1989;96(3):232-241.
17. Shroff B, Lindauer SJ, Burstone CJ, Leiss JB. Segmented approach to simultaneous intrusion and space closure: biomechanics of the three-piece base arch appliance. *Am J Orthod Dentofacial Orthop.* 1995;107(2):136-143.
18. 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.
19. Savage A, Eaton KA, Moles DR, Needleman I. A systematic review of definitions of periodontitis and methods that have been used to identify this disease. *J Clin Periodontol.* 2009;36(6):458-467.
20. Bourauel C, Freudenreich D, Vollmer D, Kobe D, Drescher D, Jäger A. Simulation of orthodontic tooth movements. A comparison of numerical models. *J Orofac Orthop.* 1999;60(2):136-151.
21. Verdonschot N, Fennis WM, Kuijs RH, Stolk J, Kreulen CM, Creugers NH. Generation of 3-D finite element models of restored human teeth using micro-CT techniques. *Int J Prosthodont.* 2001;14(4):310-315.
22. Cattaneo PM, Dalstra M, Frich LH. A three-dimensional finite element model from computed tomography data: a semi-automated method. *Proc Inst Mech Eng H.* 2001;215(2):203-213.
23. Cattaneo PM, Dalstra M, Melsen B. The finite element method: a tool to study orthodontic tooth movement. *J Dent Res.* 2005;84(5):428-433.
24. Nishihira M, Yamamoto K, Sato Y, Ishikawa K, Natali A. Mechanics of periodontal ligament. In: Natali A, ed. *Dental Biomechanics.* London: Taylor and Francis; 2003:20–34.

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25. Dorow C, Krstin N, Sander FG. Determination of the mechanical properties of the periodontal ligament in a uniaxial tensional experiment. *J Orofac Orthop.* 2003;64(2):100-107.
26. Cattaneo PM, Dalstra M, Melsen B. Moment-to-force ratio, center of rotation, and force level: a finite element study predicting their interdependency for simulated orthodontic loading regimens. *Am J Orthod Dentofacial Orthop.* 2008;133(5):681-689.
27. Viecilli RF, Budiman A, Burstone CJ. Axes of resistance for tooth movement: does the center of resistance exist in 3-dimensional space? *Am J Orthod Dentofacial Orthop.* 2013;143(2):163-172.
28. Oh MB, Mo SS, Hwang CJ, Chung C, Kang JM, Lee KJ. The 3-dimensional zone of the center of resistance of the mandibular posterior teeth segment. *Am J Orthod Dentofacial Orthop.* 2019;156(3):365-374.
29. Geramy A. Alveolar bone resorption and the center of resistance modification (3-D analysis by means of the finite element method). *Am J Orthod Dentofacial Orthop.* 2000;117(4):399-405.
30. Cobo J, Argüelles J, Puente M, Vijande M. Dentoalveolar stress from bodily tooth movement at different levels of bone loss. *Am J Orthod Dentofacial Orthop.* 1996;110(3):256-262.
31. Cobo J, Sicilia A, Argüelles J, Suárez D, Vijande M. Initial stress induced in periodontal tissue with diverse degrees of bone loss by an orthodontic force: tridimensional analysis by means of the finite element method. *Am J Orthod Dentofacial Orthop.* 1993;104(5):448-454.
32. Agarwal A, Mahajan S, Verma S, Bhardwaj P, Sharma G. Evaluation of the Stress Induced in Tooth, Periodontal Ligament & Alveolar Bone with Varying Degrees of Bone Loss During Various Types of Orthodontic Tooth Movements. *J Clin Diagn Res.* 2016;10(2):ZC46-52.
33. Viecilli RF, Kar-Kuri MH, Varriale J, Budiman A, Janal M. Effects of initial stresses and time on orthodontic external root resorption. *J Dent Res.* 2013;92(4):346-351.
34. Viecilli RF, Katona TR, Chen J, Hartsfield JK, Roberts WE. Orthodontic mechanotransduction and the role of the P2X7 receptor. *Am J Orthod Dentofacial Orthop.* 2009;135(6):694.e691-616; discussion 694-695.
35. Kawarizadeh A, Bourauel C, Zhang D, Götz W, Jäger A. Correlation of stress and strain profiles and the distribution of osteoclastic cells induced by orthodontic loading in rat. *Eur J Oral Sci.* 2004;112(2):140-147.
36. Wu J, Liu Y, Zhang J, Peng W, Jiang X. Biomechanical investigation of orthodontic treatment planning based on orthodontic force measurement and finite element method before implementation: A case study. *Technol Health Care.* 2018;26(S1):347-359.

TABLES

Table 1. The measurements are the differences (in mm) of the vertical displacements between the apex and incisal edge nodes. The smallest number, in bold, is indicative of the point of application of

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the force in which the movement is closest to a clinical translation in the vertical direction (Z-axis). CI: central incisor; LI: lateral incisor.

	Normal		Mild		Moderate		Severe	
Force Application	CI	LI	CI	LI	CI	LI	CI	LI
V1	0.010	0.009	-0.027	-0.025	-0.047	-0.042	-0.062	-0.058
V2	0.008	0.008	-0.022	-0.021	-0.038	-0.033	-0.053	-0.050
V3	0.007	0.006	-0.014	-0.014	-0.032	-0.028	-0.042	-0.040
V4	0.005	0.005	-0.010	-0.010	-0.019	-0.018	-0.024	-0.023
V5	0.003	0.003	-0.005	-0.005	-0.008	-0.008	-0.007	-0.007
V6	**-0.000**	**0.001**	**0.002**	**0.001**	**0.002**	**0.000**	**0.003**	**0.002**
V7	-0.002	-0.001	0.016	0.013	0.013	0.010	0.015	0.013
V8	-0.004	-0.002	0.020	0.017	0.025	0.020	0.038	0.035
V9	-0.005	-0.003	0.028	0.024	0.035	0.029	0.052	0.048
V10	-0.007	-0.005	0.033	0.029	0.043	0.036	0.060	0.055

Table 2. The measurements are the differences (in mm) of the sagittal displacements between the apex and incisal edge nodes. The smallest number, in bold, is indicative of the point of application of the force generating a movement, which is closest to a clinical translation in respect to the horizontal direction (Y-axis). CI: central incisor; LI: lateral incisor.

	Normal		Mild		Moderate		Severe	
Force Application	CI	LI	CI	LI	CI	LI	CI	LI
D1	-0.084	-0.073	-0.275	-0.244	-0.395	-0.359	-0.619	-0.549
D2	-0.072	-0.061	-0.258	-0.227	-0.376	-0.340	-0.568	-0.504
D3	-0.062	-0.051	-0.222	-0.195	-0.353	-0.318	-0.517	-0.456
D4	-0.044	-0.034	-0.203	-0.176	-0.329	-0.295	-0.488	-0.429
D5	-0.021	-0.014	-0.175	-0.148	-0.299	-0.265	-0.427	-0.372
D6	**-0.005**	**0.001**	-0.145	-0.119	-0.258	-0.225	-0.376	-0.324
D7	0.010	0.016	-0.094	-0.071	-0.194	-0.163	-0.301	-0.256
D8	0.027	0.032	-0.033	**-0.014**	-0.138	-0.107	-0.192	-0.158
D9	0.040	0.045	**0.005**	0.021	-0.024	**-0.006**	-0.095	-0.072
D10	0.047	0.051	0.031	0.045	**0.016**	0.031	**-0.022**	**-0.006**

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FIGURE LEGENDS

Figure 1. A µCT-image of the anterior maxilla used to generate the 3D FE model of intact periodontal dentition (step 1), from which the periodontal reduced models were created to represent a mild (- 2 mm), moderate (-4 mm), and severe (-6 mm) alveolar bone loss conditions – step2.

Figure 2. Intrusion loading regime with 10 points of force application, from 1 to 10 mm away from the bracket of lateral incisor in the vertical direction (A) and distalization loading regime with 10 points of force application, from 1 to 10 mm away from the bracket of lateral incisor in the horizontal direction (B). For both regimens, normal and reduced loads (-20%) were applied in all vertical (V1-V10) and horizontal points (D1-D10).

Figure 3. INTRUSIVE MECHANICS: Tooth displacements in the vertical axis (Z-axis) during the application of intrusive forces in the "ideal" point established by both numerical and graphic methods for CR estimation. The clinical CR for intrusion of the four anterior teeth was localized along the same line of action of the force, applied at 6 mm (V6) from the lateral bracket, in the four models evaluated. RETRACTION MECHANICS: Tooth displacements in the sagittal axis (y-axis) during the application of retraction forces in the "ideal" points established by both numerical and graphic methods for CR estimation. The clinical CRs for pure distal translation of the four anterior teeth were localized along different lines of action of the forces, depending on the degree of alveolar bone loss. The "ideal" point for the normal model was D6 (6 mm from the bracket of lateral incisor); The "ideal" points for mill, moderate and severe models were D8, D9 and D10, respectively. In both intrusive and retraction mechanics, note that the displacement's indicative colors are distributed in a homogeneous manner along the surface of teeth's elements (10X magnification). The before and after comparisons (shadow vs. solid shape) also show the characteristic root parallelism of translation.

Figure 4. PDL radial strains induced by intrusive forces applied at the "ideal" point (V6 in all models) for genuine intrusion or by retraction forces applied at the "ideal" points for pure translation in normal (point D6), mild (point D8), moderate (point D9) and severe (point D10) models. Blue labels represent the compressive negative strains (minimum value) and the red labels represent the tensile positive strains (maximum value) in the PDL of central and lateral incisors. This image shows the comparisons between the PDL strains induced by conventional forces (40 g/side for intrusion and 100 g/side for retraction – A) and reduced forces (30g/side for intrusion or 80 g/side for retraction – B).

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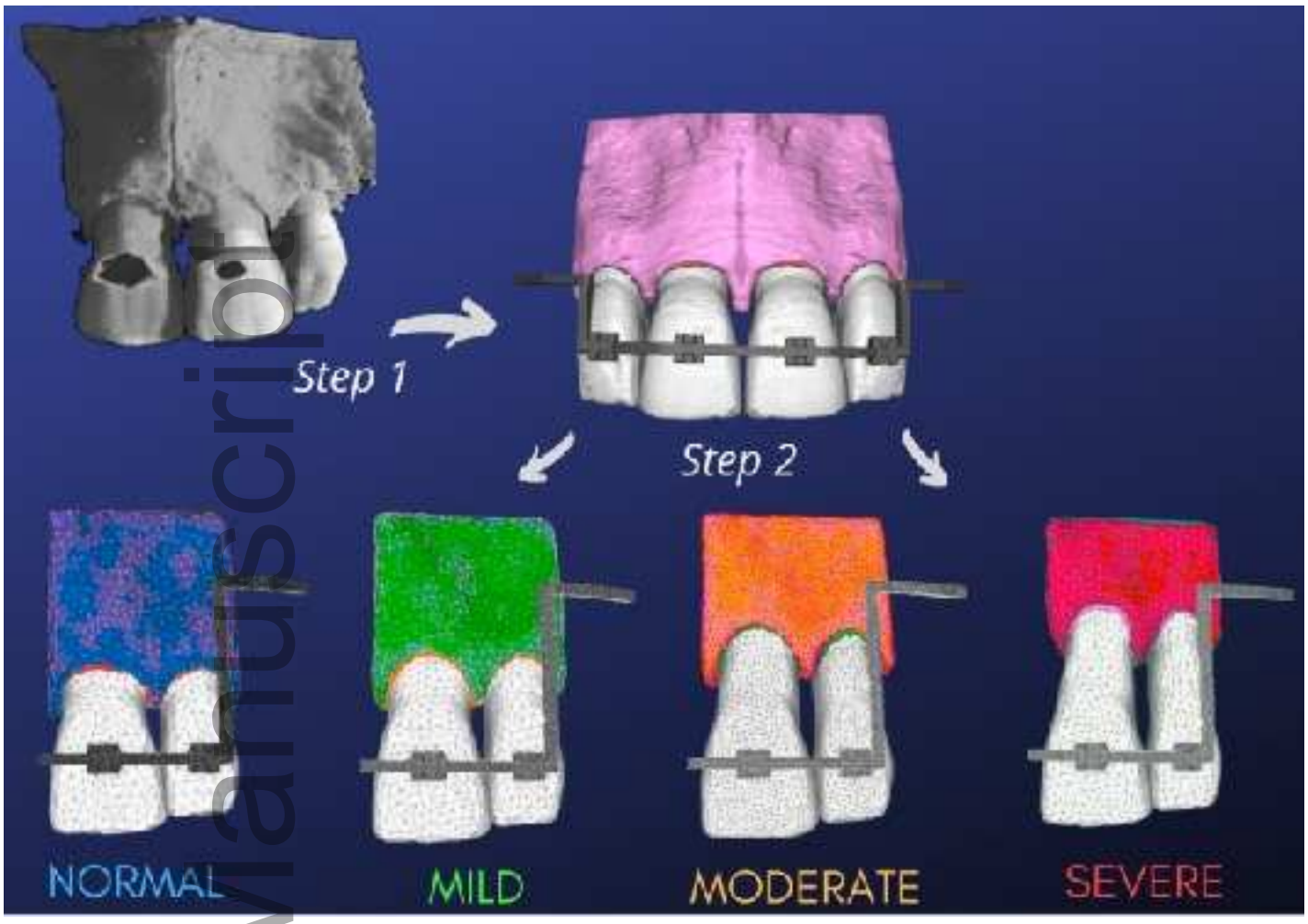

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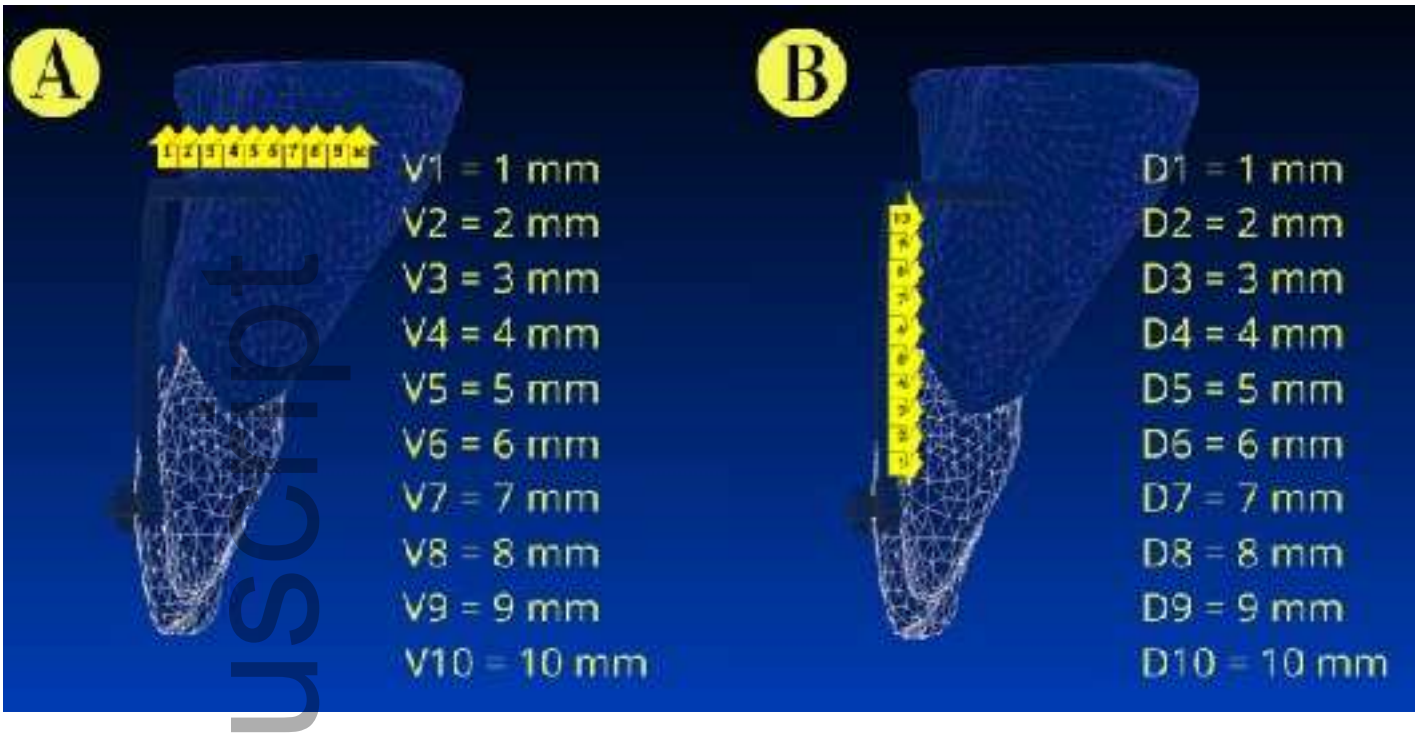

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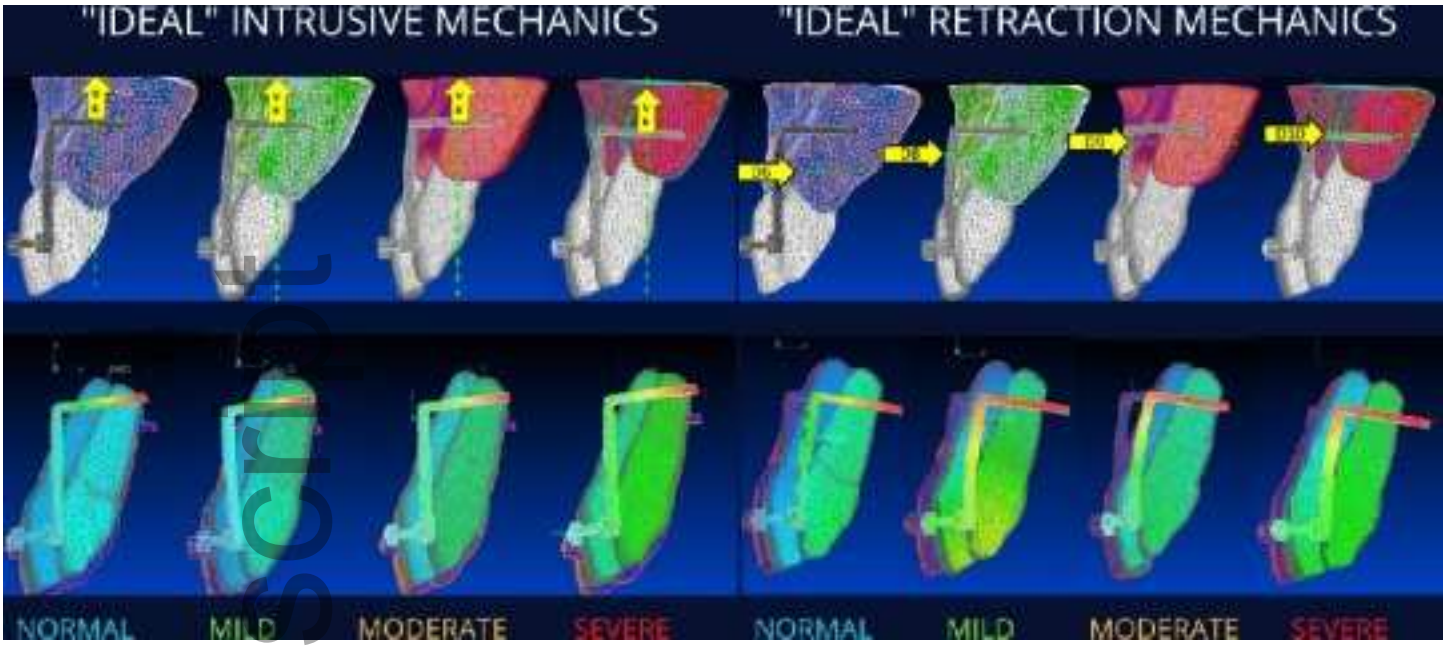

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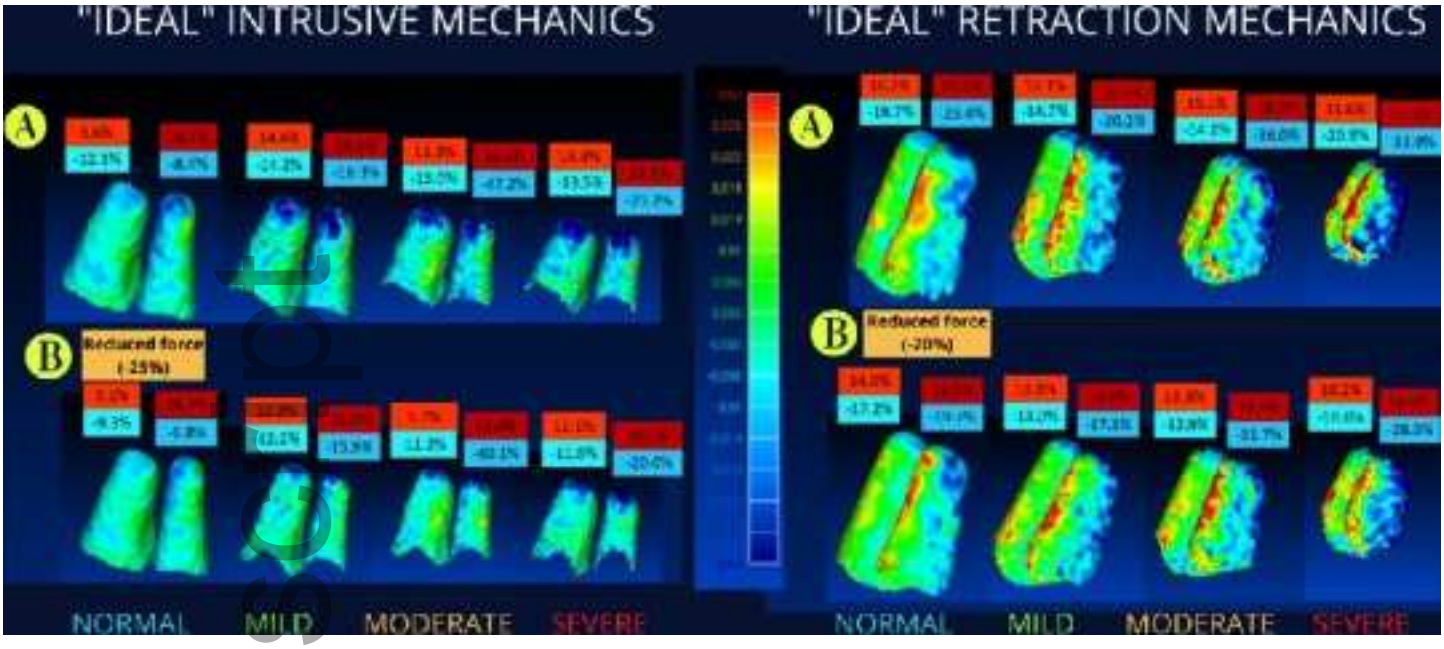

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