ORIGINAL RESEARCH

# A New Proposal for Calibrated Gauges for Removable Partial Dentures: A Finite Element Analysis

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## Abstract

**Aim:** The aim of this study was to evaluate the stress distribution of a planned removable partial denture (RPD) using new proposals for calibrated gauges of 0.3 mm and 0.35 mm undercuts through the three-dimensional (3D) finite element methodology, and compare them with 0.25 mm and 0.5 mm gauges that are already existing in clinical practice.

**Materials and methods:** Kennedy class-I edentulous 3D models and their respective RPDs (InVesalius software; Rhinoceros and SolidWorks CAD) were created and exported to the finite element program HyperMesh 2019 for mesh configuration. In the following steps, axial loading (0º) of 40 N per point was performed, with 3 points on the molars and 2 points on the premolars, totaling 280 N unilaterally. The model was processed by the OptiStruct 2019 software and imported into the HyperView 2019 software to obtain the stress maps (MPa).

**Results:** The use of 0.30 and 0.35 mm calibrated gauges presented tensions similar to those with the 0.25 mm gauge (gold standard) and caused no significant damage to biological structures. The use of a 0.5 mm undercut caused greater traction force in the periodontal ligament of the abutments.

**Conclusions:** The 0.35 mm undercut seems promising as it presented more favorable results in this simulation, on the other hand, a 0.5 mm undercut is greater than that necessary for retainers made of CoCr.

**Clinical significance:** This study aims to measure a new undercut gauge (0.35 mm) to increase the retention area in abutment teeth of removable partial dentures.

**Keywords:** Crowns, Dental clasps, Dental prosthesis design, Finite element analysis, Removable partial denture.

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## Introduction

The removable partial denture (RPD) presents with advantages such as replacement of several elements in a single piece, low cost, and easy access.[1–3] For correct planning, the study of cast models in a surveyor is necessary.[4–7] This instrument allows the analysis of inclination and retention of abutment teeth, making it possible to determine the path of insertion, guide planes, undercut, and correct position of each RPD component.[8–10]

The appropriate retention of abutments is determined by the calibrated gauge in the surveyor. An ideally retained RPD should hamper the gingival–occlusal movement without showing great resistance to its removal.[11,12] The calibrated gauges are usually manufactured in three different undercuts, i.e., 0.25 mm, 0.50 mm, and 0.75 mm,[13,14] and used according to the framework material. The 0.25 mm undercut is the gold standard for the cobalt–chromium (CoCr) alloy.[12,15]

The continuous process of insertion and removal, associated with the biomechanics of RPDs during the time of use, can cause damage to abutments and supporting tissues, thereby leading to bone resorption, dental mobility, gingival retraction, and even tooth loss. These consequences negatively affect chewing, phonation, esthetics, and the quality of life[16–19] and might be due to lack of or higher retention.[20,21]

Several studies demonstrated that RPD clasps lose retention with continuous use.[12,22–24] Initially, they present with adequate retention; however, with the continuous process of insertion and removal ally to masticatory cycles, the clasp loses some of its retentive strength. In addition, some variables can interfere with the predictability of RPD. For example, *in vitro* studies cannot replicate the clinical condition.[12,25,26] It is suspected that a calibrated gauge with a larger diameter could be more beneficial, offering more retention without damaging the bone tissue or PDL.

Whether an undercut with an intermediate value for CoCr frames would be viable for clinical use, presenting with biomechanical advantages such as increased retention and no damage to

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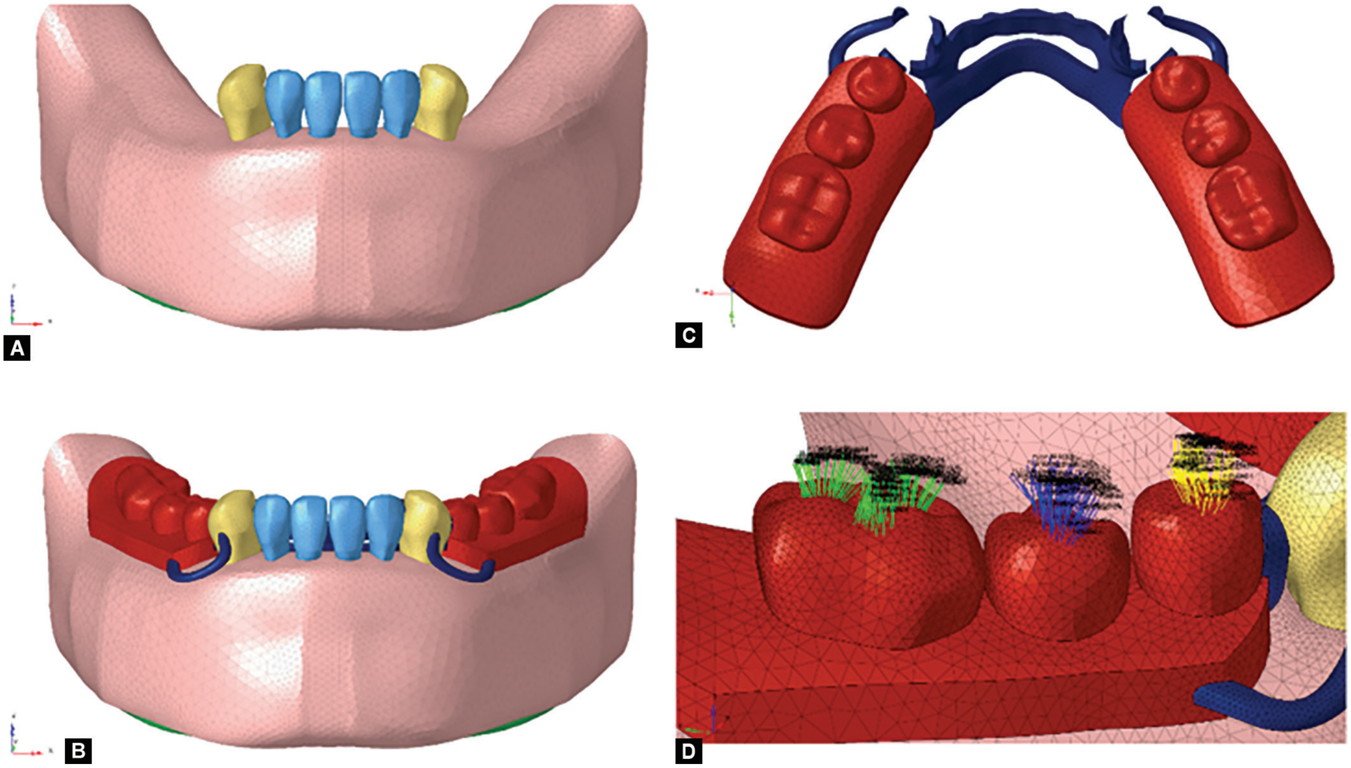
**Conflict of interest:** None




**Figs 1A to D:** (A) Three-dimensional model simulating Kennedy's class-I arc; (B) Planned RPD; (C) RPD positioned on the model; and (D) Simulation of occlusal forces: 40 N per point (total 280 N)

biological tissues, remains unclear.[12,22,26] Therefore, further studies are warranted to determine the best clinical condition and the calibrated gauge. In this context, 3D finite element methodology is important because it allows a biomechanical analysis of the stress distribution in bone tissue structures and adjacent elements, as well as in metallic elements, making it easier to assess the magnitude of tension in different perspectives and cuts.[27–29]

The present study aims to evaluate a new proposal for retaining calibrated gauges with dimensions of 0.3 mm and 0.35 mm, comparing them with 0.25 mm and 0.5 mm tips, to verify the distribution of stresses in the RPD structures (von Mises) and adjacent bone tissue (principal stress) by finite element analysis. The new undercut gauges with an increase of 20% (0.3 mm) and 40% (0.35 mm) were designed based on the standard model (0.25 mm). The null hypothesis is that there is no biomechanical damage using 0.3 and 0.35 mm undercuts when compared with 0.25 and 0.5 mm undercuts.

## Materials and Methods

### Experimental Design

The experimental design follows previous studies.[27,30] Four models were proposed based on the diameter of the calibrated gauge (0.25, 0.3, 0.35, and 0.5) to enable the analysis of the stress distribution with different levels of retention and comparing it with the gold standard for CoCr alloys (0.25) (Table 1). The study was developed by researchers from Bauru Dental School – University of Sao Paulo and Nucleus of Three-Dimensional Technologies, Renato Archer Information Technology Center – CTI from 2019 to 2022.

### Three-dimensional FE Modeling

For the execution of this methodology, the following materials were used: computer (64-bit system, six cores, 64 GB of RAM, 1 TB of HD), assisted design programs: Rhinoceros 3D (NURBS Modeling for Windows, USA), HyperMesh 2019 simulation program on the HyperWorks platform (Altair, Troy, Michigan, USA), OptiStruct 2019 processing software (Altair, Troy, Michigan, USA), and HyperView visualization software (Altair, Troy, Michigan, USA).

A 3D model simulating a Kennedy class-I arch (bilateral toothless) was designed in computer-aided design (CAD) (Fig. 1A). Subsequently, the RPD was planned according to the standards established in the literature and then designed in the software (Fig. 1B). Four infrastructure models were designed, simulating the use of calibrated gauges of 0.25 (A25), 0.3 (B30), 0.35 (C35), and 0.5 mm (D50) (Fig. 1C), comprising of 4 groups and 4 finite elements analyses (Table 1).

The finished 3D model, including cortical bone, sponge bone, dentin, periodontal ligament, residual ridge mucosa, resin, and RPD (Co–Cr alloy), was exported to the HyperMesh 2019 finite element program to prepare the finite element meshes using the solid tetrahedral element. The mechanical properties of the simulated materials were inserted into the software (Table 2). The structure was fixed on the lateral surfaces (*x*- *y*- and *z*-axes), while the base was free or suspended. Specifically, the mesial surface was fixed only on the *x*-axis due to the model's symmetry. Thus, the rest of the model remained under the action of the applied forces and with the possibility of movement and distribution of tensions. The simulated contacts were of the glued type, except for the frame in the region of the clasps being a contact of the sliding type.

**Table 1:** Proposed experimental design

| *Kennedy's classification* | *Framework alloy* | *Undercut* |
|---|---|---|
| Class I | CoCr | 0.25 |
| | | 0.30 |
| | | 0.35 |
| | | 0.50 |

**Table 2:** Material properties of finite element models

| *Material* | *Elastic modulus (MPa)* | *Poisson ratio* | *References* |
|---|---|---|---|
| Cortical bone | 11,760 | 0.25 | Nakamura et al., 2014[37] |
| Sponge bone | 1,470 | 0.3 | Nakamura et al., 2014[37] |
| Periodontal ligament | 9.8 | 0.45 | Mizuno et al., 2016[31] |
| Residual ridge mucosa | 680 | 0.45 | Verri et al., 2011[29] |
| Resin | 2,450 | 0.3 | Nakamura et al., 2014[37] |
| Co–Cr alloy | $2 \times 10^5$ | 0.30 | Mizuno et al., 2016[31] |
| Dentin | 18,600 | 0.35 | Nakamura et al., 2014[37] |

A 40-N unilateral force was applied per point, with 3 points on the molar and 2 points on the premolars simulating a masticatory force of 280 N (Fig. 1D).

### Analysis of the Stress Distribution

The results were evaluated using principal stress maps for friable materials, such as bone structure, the unit of measurement was megapascals (MPa). The displacement was plotted in values expressed in millimeters (mm). Finally, the von Mises stress analysis was designed to interpret the total sum of stresses in specific metallic regions. A particular analysis of different structures (metal framework, periodontal ligament, mandible bone, and alveolar bone) was executed to make a comparison between the proposed groups.[27,30,32]

## Results

### Metal Framework

In an analysis of the von Mises stresses for the metallic frame, it was possible to verify that the highest intensity of stress was in the transition region between the saddle and the lingual bar, existing over an area of concentration in the range of 1.33E + 00 MPa, as well as on the proximal plate and in the center of the lingual bar for all models (Figs 2A–P).

On a closer view, the proximal plate was seen through an internal view in the region that comes into contact with the column, where the stress in the different models was similar. The stress was higher (2.00E + 00 MPa) in the upper region. Models C35 and D50 had smaller total areas of tension on the proximal plate (Figs 2I–L).

Regarding the retainers, there was no significant difference in the stress distribution in this simulation. Notably, group D50 (Fig. 2H) presented with a higher-intensity stress at the tip of clasp I (4.4E-01 to 8.8E-01 MPa).

### Periodontal Ligament

In maximum principal stress (MPS) analysis (Figs 3A–P), there was a similar pattern of stress distribution for models A25, B30, and C35; however, model D50 had a larger area of tension in teeth pillars than the others (–1.6 to 6.6 MPa, Figs 3A–D). Groups A25, B30, and C35 showed areas of higher compression than D50 on the distal face of elements 33 and 43 (Figs 3D and L). However, in groups A25, B30, and C35, there was more traction in the mesial region of the PDL (element 33) than model D50 (Figs 2E–G). The group C35 presented with higher compression in the mesial region of 43 abutments (Fig. 3C).

In the root apex region, models A25, B30, and C35 demonstrated regions of compression in the root apices of elements 33 and 43 (–2.6 to –1.8 MPa), while model D50 showed an area of more traction (–1.6 to 6.6 MPa). In the other elements (32, 31, 41, and 42), the values between the groups were similar.

### Mandible Bone

In the mandible bone (Figs 4A–D), the greatest stress (3.7–4.4 MPa) was concentrated on the right side where the force was applied in the region where the simulated RPD saddle ended, but no differences were observed in relevant values between groups.

### Alveolar Bone

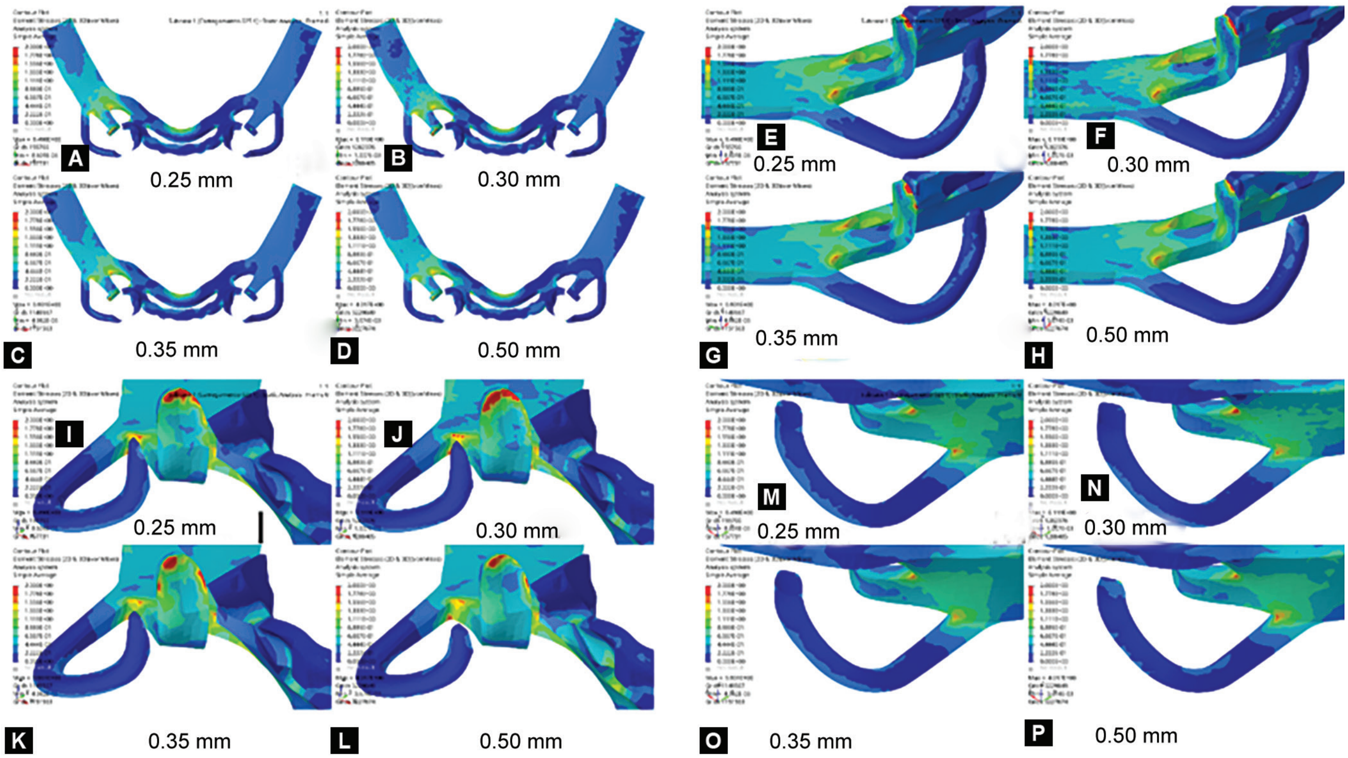
In the alveolar bone (Figs 5A–D), model D50 represented the group with the largest area and highest tensile stress value in the alveolar bone on the side contralateral to the applied force, buccal wall of the alveolus of element 33 (1.6–2.3 MPa), and compression areas in the mesial region (–6.2 to 0.1 MPa). In contrast, models A25, B30, and C35 demonstrated traction area in the vestibulo-mesial region (0.8–1.6 MPa). In element 43, adjacent to the force applied in the simulation, models A25, B30, and C35 demonstrated similar values with higher compression in the distal region (–6.2 to 0.1 MPa) when compared with group D50 (0.1–0.8 MPa).

In general, the use of a 0.5 mm undercut caused greater traction force in retainers, periodontal ligament of the abutments (apical region), and alveolar bone. The 0.3 mm and 0.35 mm undercut options showed a similar distribution when compared with the control group (0.25 mm).

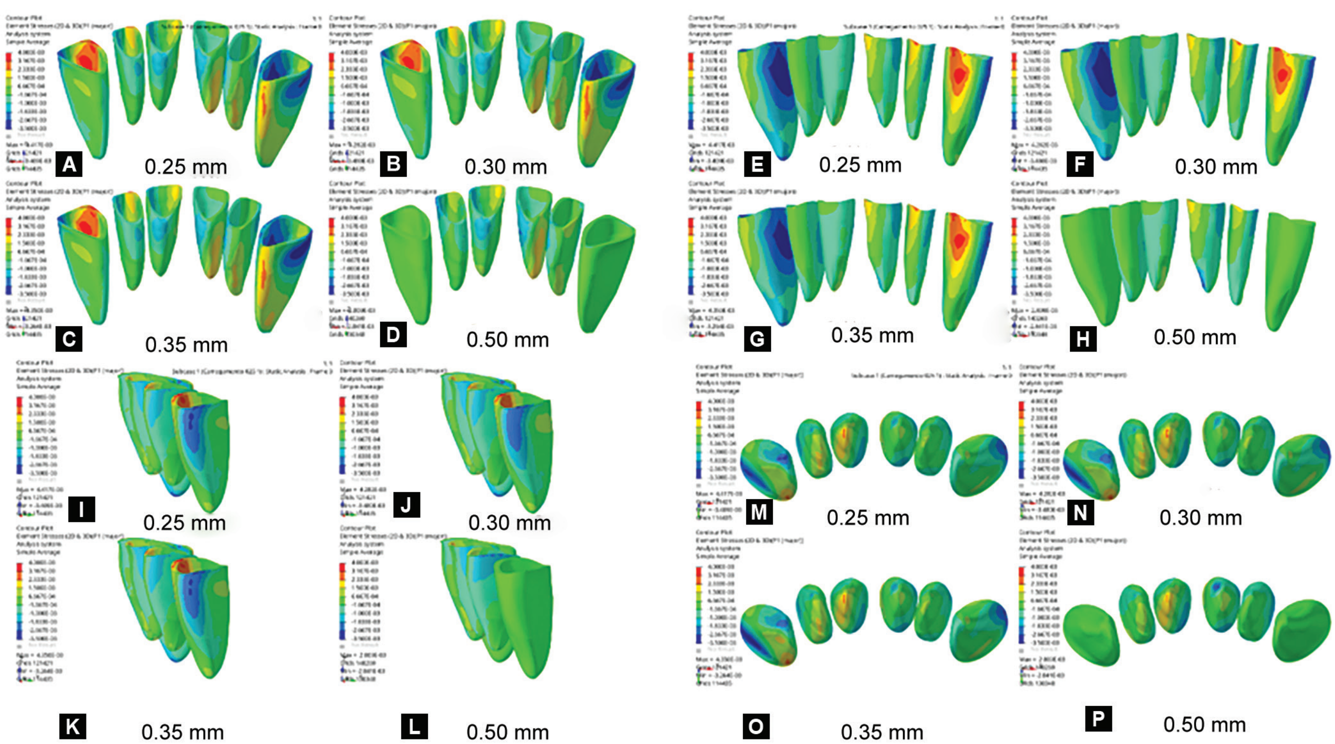
## Discussion

Removable partial denture is a frequently used treatment modality in the dental clinic. The loss of posterior teeth is a routine clinical condition, where rehabilitation with RPD class I requires support not only of the teeth but also of the alveolar ridge. This biomechanical lever of functional interaction requires good support and adequate planning to protect tissues, and, at the same time, promote function. The aim of this study was to investigate whether the increase in retention in RPDs with two new proposals for calibrated gauges would generate responses similar to biological tissues compared with the gold standard of 0.25 mm for frames in CoCr. The null hypothesis was confirmed, with similarities in groups A25, B30, and C35 in the simulation. This means that the tested calibrated gauges, 0.30 and 0.35 mm, with more retention, caused biomechanical responses similar to the 0.25 mm undercut without major damage to the teeth, periodontium, or bone tissue. In contrast, the D50 model, with a 0.5 mm undercut, showed the most divergent results, especially in the periodontal tissue analysis, with a greater area of tensile stress (–1.6 to 6.6 MPa) in the abutments (33 and 43) than the other groups.

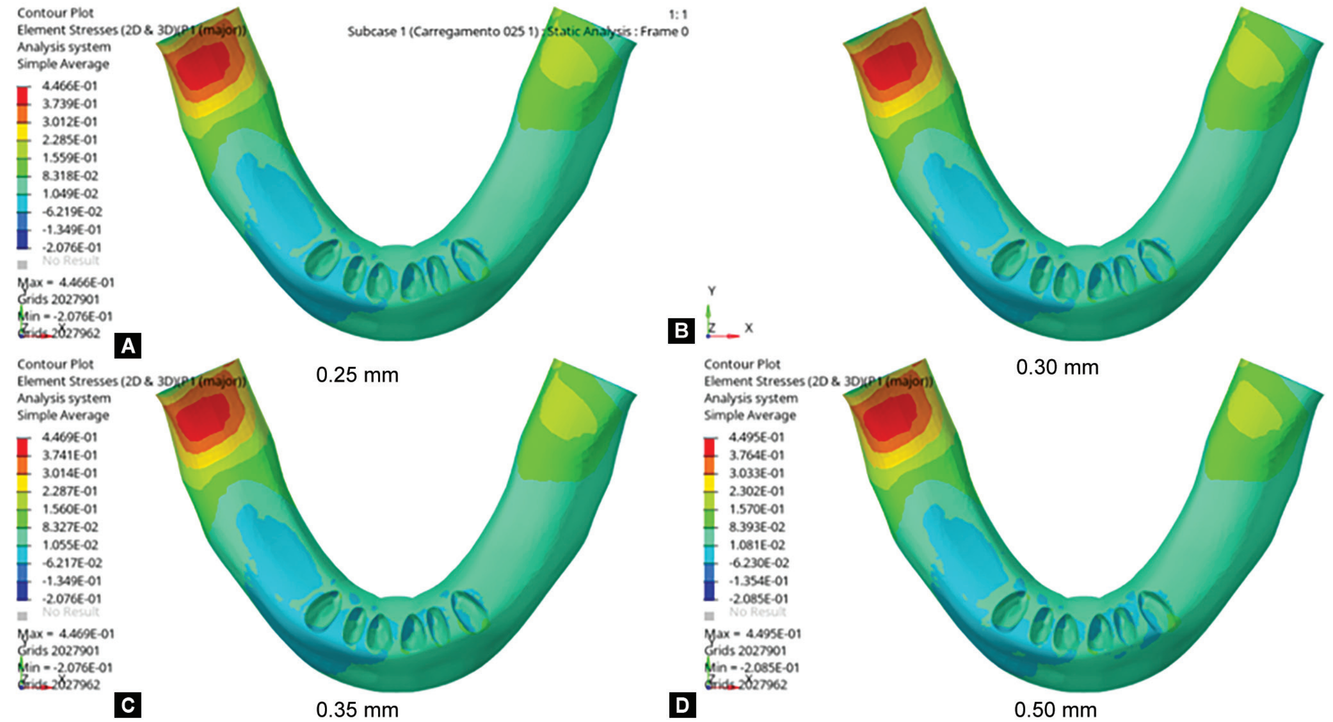
In this context, the study of retention is a relevant point for removable prostheses. Cheng et al.[12] described the properties of the CoCr alloy with insertion and removal tests under calibration of 0.25 mm and 0.5 mm, observing the retentive strength in each



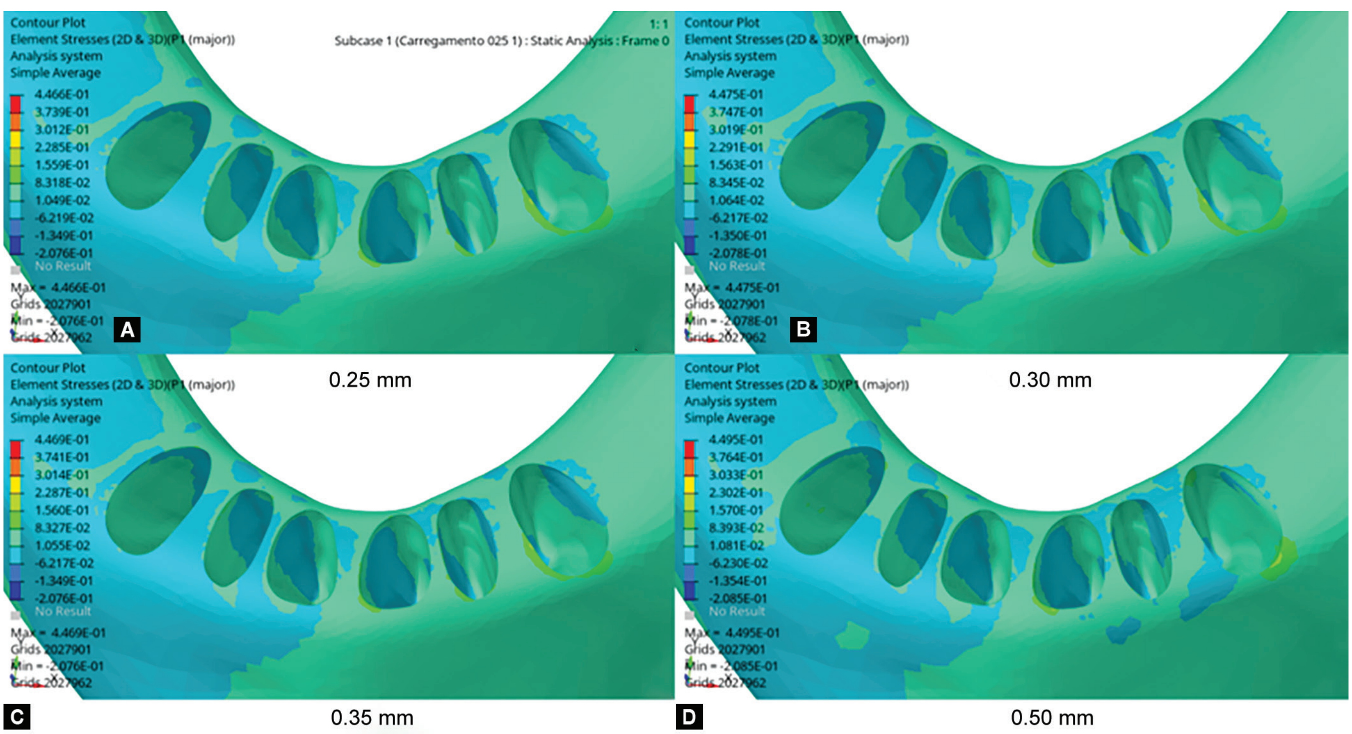

**Figs 2A to P:** Metal framework (calibrated gauges of 0.25, 0.3, 0.35, and 0.5 mm) with visualization of regions of interest: (A–D) Occlusal view; (E–H) Right-side dental clasp, buccal view; (I–L) Right-side proximal plaque, internal view; and (M–P) Right-side dental clasp, lingual view




**Figs 3A to P:** Periodontal ligament (calibrated gauges of 0.25, 0.3, 0.35, and 0.5 mm) with visualization of regions of interest: (A–D) Lingual view; (E–H) Buccal view; (I–L) Left-side view; (M–P) Root apex view




**Figs 4A to D:** Mandible bone with visualization of occlusal view: (A) A25 group; (B) B30 group; (C) C35 group; and (D) D50 group




**Figs 5A to D:** Alveolar bone with visualization of occlusal view: (A) A25 group; (B) B30 group; (C) C35 group; and (D) D50 group

cycle, where retention decreased dramatically after the first test cycle in all groups and continued to decrease in the following phases. They also described that the retentive force was greater in the 0.5 mm group, but the permanent deformation of the metallic alloy would invariably occur, highlighting that the proportional limit of deformation of the material would be greater than 0.25 and less than 0.5 mm. However, no removal test was performed in this study, which is one of its limitations.

Alageel et al.[33] stated that the inadequate infrastructure of an RPD, specifically clasps, results in insufficient retention, which is one of the main aspects of patient dissatisfaction. The authors carried out retention tests in an *in vitro* study, with the objective of obtaining ideal retention, and described the loss of retention of metallic clasps in all groups (wrought wire, circumferential, and I-bar). In agreement with these results, other studies also described the significant loss of retention of metal clasps using 0.25 and 0.5 mm undercuts using different clinical situations.[21–25] These authors analyzed this effect in situations: natural fresh saliva,[21] clasp material (acetate, resin, Co–Cr, Ag–Pd, Gold, and Ti–Ni alloys),[22,24,25] changes in the dental abutment with composite resin-recontoured,[23] and prosthesis material (monolithic zirconia and Ag–Pd full-metal crowns).[24]

In addition to adequate retention, RPD must have reasonable esthetics and cause minimal trauma to the remaining tissues. When inadequate planning and displacements outside the expected standards occur, the incorrect movement of the denture can cause even more damage to dental elements and supporting tissues. The poor condition of the abutment and changes in PDL caused by improper stress affect the beneficial effect of rehabilitation. Therefore, planning is essential and must consider not only retention and esthetics but also tension in the abutment and oral tissues.

The PDL is a thin membrane of the conjunctive tissue, and its physiological and pathological responses are distinct across individuals. Its physiology is difficult to study because the PDL is extremely thin, delicate, and complex. Its biomechanical behavior is still not well understood despite being studied for over a hundred years, and there is no consensus in the literature about its stress limits. Since stress in the human periodontium is difficult to measure clinically, it remains unclear as to what extent the forces of an RPD are acting on that tissue.[34–36] Despite this, some authors have described the biomechanical behavior of the PDL with RPDs, using the finite element methodology. Muraki et al.[34] applied vertical load to the supports of an RPD and observed that the maximum tension in the PDL was 0.35 MPa. According to the authors, the displacements and tensions were relatively small and were all within the physiological limitations of the tissues, being less than the critical stress, which may be harmful for the bone.

Similarly, Nakamura et al.[37] described the stress in the supporting tissues simulating a Kennedy class-II RPD under 200 N load (40 N per point). The authors simulated different clasps on the abutment teeth and concluded that the class-I clasp, which was used in the simulation of the present study, demonstrated the lowest stress in the PDL of the direct abutment (second premolar) and minimum tension in the PDL of the first premolar, being well indicated for regions without posterior support.

Some studies sought to analyze the stress distribution in the periodontium in different clinical situations. Ortiz-Puigpelat et al.[38] described, through the von Mises analysis, stress in the PDL while simulating an oblique masticatory force of 200 N on RPDs with and without implants in the posterior region. They observed that the highest tension in the PDL was found in the control group, without implants (27%); however, the values were very similar between all models (0.101–0.105 MPa). Chen et al.[39] simulated a class-I RPD and, by using von Mises analysis, obtained maximum stress of the PDL of 0.17 ± 0.01 MPa for frames in CoCr. A vertical load of 120 N was applied to the occlusal surface of the first molars.

The authors mentioned above described the biomechanical behavior of the PDL with finite elements and removable prostheses in their studies. In the present study, the stress was very similar between the groups when the metal frame was compared by the analysis of von Mises in the ridge and the alveolar bone. However, the groups showed differences when the PDL was compared. In group D50, during an analysis of the main maximum stress, the PDL showed an average traction of 1.6–6.6 MPa in the columns without compression regions. In contrast, groups A25, B30, and C35 demonstrated areas of traction and compression according to the direction of the unilateral load applied. While the direct and distal pillars suffered compression, there was traction on the opposite side, since the force applied on the other side would cause the same effect, such as functional chewing.

No previous study has introduced new calibrated gauges in simulations for a possible increase in nonharmful retention. In the present study, the tension maps of the metallic frame and biological tissues were very similar in the four groups, except in the PDL, where group D50 presented with the highest area of traction in the pillar elements 33 and 43, indicating that this group would possibly cause greater trauma to abutments than the other groups. However, further studies are needed to confirm these findings. This does not preclude the use of other gauges but increases the possibility that greater retention is specifically directed to different materials with the largest elastic module for making the framework. This process can be facilitated, for example, with the advent of CAD and computer-aided manufacturing (CAD–CAM) technology and the use of new materials in dentistry.

Different studies describe the relationship between RPD and oral tissues in different ways, presenting different objectives, methodologies, prosthesis design, pillar tooth, unilateral or bilateral strength, infrastructure material, and mathematical analyses. In this respect, comparing the results is difficult, requiring further studies in the area. It is prudent to seek the best methodology for modeling and analysis of stress involving finite elements since the mathematical data follow the pattern of computational information that was previously established and may result in highly variable components depending on the methodology used.

## Conclusion

The 0.30 and 0.35 mm calibrated gauges presented tissue tensions similar to the 0.25 mm gold standard, causing no more significant damage to biological structures, indicating that it is possible to increase retention using these undercuts without causing the increase in stress areas in the abutment teeth and surrounding structures.

The 0.35 mm undercut was promising as it presented with more favorable results in this simulation, but further studies are necessary to confirm these findings.

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## References

1. Jones JD, Turkyilmaz I, Garcia LT. Removable partial dentures–treatment now and for the future. Tex Dent J 2010;127(4):365–372. PMID: 20446487
2. Bohnenkamp DM. Removable partial dentures: Clinical concepts. Dent Clin North Am 2014;58(1):69–89. DOI: 10.1016/j.cden.2013.09.003.

3. Campbell SD, Cooper L, Craddock H, et al. Removable partial dentures: The clinical need for innovation. J Prosthet Dent 2017;118(3):273–280. DOI: 10.1016/j.prosdent.2017.01.008.
4. Bezzon OL, Mattos MG, Ribeiro RF. Surveying removable partial dentures: The importance of guiding planes and path of insertion for stability. J Prosthet Dent 1997;78(4):412–418. DOI: 10.1016/s0022-3913(97)70051-9.
5. de Aquino AR, Barreto AO, de Aquino LM, et al. Longitudinal clinical evaluation of undercut areas and rest seats of abutment teeth in removable partial denture treatment. J Prosthodont 2011;20(8): 639–642. DOI: 10.1111/j.1532-849X.2011.00766.x.
6. Sayed ME, Busaily IA, Nahari RJ, et al. Evaluation of cast re-orientation on a dental surveyor using three tripod techniques: A survey and in vitro study. J Prosthodont 2018;27(8):700–707. DOI: 10.1111/jopr.12581.
7. Lee H, Kwon KR. A CAD-CAM device for preparing guide planes for removable partial dentures: A dental technique. J Prosthet Dent 2019;122(1):10–13. DOI: 10.1016/j.prosdent.2018.06.011.
8. Holt JE. Guiding planes: When and where. J Prosthet Dent 1981;46(1):4–6. DOI: 10.1016/0022-3913(81)90126-8.
9. Waghorn S, Kuzmanovic DV. Technique for preparation of parallel guiding planes for removable partial dentures. J Prosthet Dent 2004;92(2):200–201. DOI: 10.1016/j.prosdent.2004.05.011.
10. Moldovan O, Rudolph H, Luthardt RG. Clinical performance of removable dental prostheses in the moderately reduced dentition: A systematic literature review. Clin Oral Investig 2016;20(7):1435–1447. DOI: 10.1007/s00784-016-1873-5.
11. Khan SB, Geerts GA. Aesthetic clasp design for removable partial dentures: A literature review. SADJ 2005;60(5):190–194. PMID: 16052751.
12. Cheng H, Xu M, Zhang H, et al. Cyclic fatigue properties of cobalt-chromium alloy clasps for partial removable dental prostheses. J Prosthet Dent 2010;104(6):389–396. DOI: 10.1016/S0022-3913(10)60173-4.
13. Davenport JC, Basker RM, Heath JR, et al. The removable partial denture equation. Br Dent J 2000;189(8):414–424. DOI: 10.1038/sj.bdj.4800787.
14. Mamoun JS. The path of placement of a removable partial denture: A microscope based approach to survey and design. J Adv Prosthodont 2015;7(1):76–84. DOI: 10.4047/jap.2015.7.1.76.
15. Tribst JPM, Dal Piva AMdeO, Borges ALS, et al. Effect of different materials and undercut on the removal force and stress distribution in circumferential clasps during direct retainer action in removable partial dentures. Dent Mater 2020;36(2):179–186. DOI: 10.1016/j.dental.2019.11.022.
16. Preshaw PM, Walls AW, Jakubovics NS, et al. Association of removable partial denture use with oral and systemic health. J Dent 2011;39(11):711–719. DOI: 10.1016/j.jdent.2011.08.018.
17. Jorge JH, Quishida CC, Vergani CE, et al. Clinical evaluation of failures in removable partial dentures. J Oral Sci 2012;54(4):337–342. DOI: 10.2334/josnusd.54.337.
18. Tada S, Ikebe K, Matsuda K, et al. Multifactorial risk assessment for survival of abutments of removable partial dentures based on practice-based longitudinal study. J Dent 2013;41(12):1175–1180. DOI: 10.1016/j.jdent.2013.07.018.
19. Tada S, Allen PF, Ikebe K, et al. Impact of periodontal maintenance on tooth survival in patients with removable partial dentures. J Clin Periodontol 2015;42(1):46–53. DOI: 10.1111/jcpe.12320.
20. Celebić A, Knezović-Zlatarić D. A comparison of patient's satisfaction between complete and partial removable denture wearers. J Dent 2003;31(7):445–451. DOI: 10.1016/s0300-5712(03)00094-0.
21. Mourshed B, Qaed NM, Al-Shamiri HM, et al. The effect of environment (dry and natural saliva) on clasp retention: *In vitro* study – Part I. Eur J Dent 2017;11(3):352–356. DOI: 10.4103/ejd.ejd_158_17.
22. Arda T, Arikan A. An *in vitro* comparison of retentive force and deformation of acetal resin and cobalt-chromium clasps. J Prosthet Dent 2005;94(3):267–274. DOI: 10.1016/j.prosdent.2005.06.009.
23. Zarrati S, Sadighpour L, Jahanian G. Comparison of clasp retention on enamel and composite resin-recontoured abutments following repeated removal *in vitro*. J Prosthet Dent 2010;103(4):240–244. DOI: 10.1016/S0022-3913(10)60037-6.
24. Tanaka A, Miyake N, Hotta H, et al. Change in the retentive force of Akers clasp for zirconia crown by repetitive insertion and removal test. J Prosthodont Res 2019;63(4):447–452. DOI: 10.1016/j.jpor.2019.02.005.
25. Kim D, Park C, Yi Y, et al. Comparison of cast Ti-Ni alloy clasp retention with conventional removable partial denture clasps. J Prosthet Dent 2004;91(4):374–382. DOI: 10.1016/j.prosdent.2004.02.015.
26. Schipper RG, Silletti E, Vingerhoeds MH. Saliva as research material: Biochemical, physicochemical and practical aspects. Arch Oral Biol 2007;52(12):1114–1135. DOI: 10.1016/j.archoralbio.2007.06.009.
27. Pellizzer EP, Verri FR, Falcón-Antenucci RM, et al. Stress analysis in platform-switching implants: A 3-dimensional finite element study. J Oral Implantol 2012;38(5):587–594. DOI: 10.1563/AAID-JOI-D-10-00041.
28. Bhering CL, Mesquita MF, Kemmoku DT, et al. Comparison between all-on-four and all-on-six treatment concepts and framework material on stress distribution in atrophic maxilla: A prototyping guided 3D-FEA study. Mater Sci Eng C Mater Biol Appl 2016;69:715–725. DOI: 10.1016/j.msec.2016.07.059.
29. Verri FR, Santiago JF Jr, Almeida DA, et al. Biomechanical three-dimensional finite element analysis of single implant-supported prostheses in the anterior maxilla, with different surgical techniques and implant types. Int J Oral Maxillofac Implants 2017;32(4):e191–e198. DOI: 10.11607/jomi.5472.
30. Santiago Junior JF, Pellizzer EP, Verri FR, et al. Stress analysis in bone tissue around single implants with different diameters and veneering materials: A 3D finite element study. Mater Sci Eng C Mater Biol Appl 2013;33(8):4700–4714. DOI: 10.1016/j.msec.2013.07.027.
31. Mizuno Y, Gonda T, Takahashi T, et al. Root Fracture of Abutment Teeth for Partial Removable Dental Prostheses. Int J Prosthodont 2016;29(5):461–466. DOI: 10.11607/ijp.4327.
32. Baggi L, Cappelloni I, Di Girolamo M, et al. The influence of implant diameter and length on stress distribution of osseointegrated implants related to crestal bone geometry: A three-dimensional finite element analysis. J Prosthet Dent 2008;100(6):422–431. DOI: 10.1016/S0022-3913(08)60259-0.
33. Alageel O, Alsheghri AA, Algezani S, et al. Determining the retention of removable partial dentures. J Prosthet Dent 2019;122(1):55–62.e3. DOI: 10.1016/j.prosdent.2018.06.015.
34. Muraki H, Wakabayashi N, Park I, et al. Finite element contact stress analysis of the RPD abutment tooth and periodontal ligament. J Dent 2004;32(8):659–665. DOI: 10.1016/j.jdent.2004.07.003.
35. Sinescu C, Duma VF, Dodenciu D, et al. Mechanical properties of the periodontal system and of dental constructs deduced from the free response of the tooth. J Healthc Eng 2018;2018:4609264. DOI: 10.1155/2018/4609264.
36. Wu B, Pu P, Zhao S, et al. Frequency-related viscoelastic properties of the human incisor periodontal ligament under dynamic compressive loading. PLoS One 2020;15(7):e0235822. DOI: 10.1371/journal.pone.0235822.
37. Nakamura Y, Kanbara R, Ochiai KT, et al. A finite element evaluation of mechanical function for 3 distal extension partial dental prosthesis designs with a 3-dimensional nonlinear method for modeling soft tissue. J Prosthet Dent 2014;112(4):972–980. DOI: 10.1016/j.prosdent.2014.03.011.
38. Ortiz-Puigpelat O, Lázaro-Abdulkarim A, de Medrano-Reñé JM, et al. Influence of implant position in implant-assisted removable partial denture: A three-dimensional finite element analysis. J Prosthodont 2019;28(2):e675–e681. DOI: 10.1111/jopr.12722.
39. Chen X, Mao B, Zhu Z, et al. A three-dimensional finite element analysis of mechanical function for 4 removable partial denture designs with 3 framework materials: CoCr, Ti-6Al-4V alloy and PEEK. Sci Rep 2019;9(1):13975. DOI: 10.1038/s41598-019-50363-1.