Journal of Dental Sciences

Volume 21 | Issue 2 Article 43

2026

The influence of the connector position placing, cement thickness and load direction on biomechanical performance of implant supported mesial cantilever: Finite element analysis

Bhrommin Toranathumkul

Ekachai Chaichanasiri

Samroeng Inglam

Available online at https://jds.ads.org.tw/journal/

Digital Commons

journal homepage: https://jds.ads.org.tw/journal/

Original Article

The influence of the connector position placing, cement thickness and load direction on biomechanical performance of implant supported mesial cantilever: Finite element analysis

Bhrommin Toranathumkul [a], Ekachai Chaichanasiri [a], Samroeng Inglam [b*]

[a] *Department of Mechanical Engineering, Faculty of Engineering, Mahidol University, Nakhon Pathom, Thailand*
[b] *Faculty of Dentistry, Thammasat University, Pathumthani, Thailand*

Received 15 September 2025; Final revision received 10 November 2025
Available online 1 April 2026

KEYWORDS
Biomechanical performance;
Cement thickness;
Connector position placing;
Finite element analysis;
Implant supported mesial cantilever

Abstract *Background/purpose:* Implant-supported cantilevers crowns (ISCCs) can be a viable alternative to avoid surgical adjunctive procedures when replacing missing teeth. The connector position placing (CPP) is crucial and can be adjusted to optimize the biomechanics which important to decision for long term success of treatment. The aim of this study was to investigate the biomechanical performance of ISCCs with different CPPs design, cement thickness and load directions.
Materials and methods: Three-dimensional finite element clinical simulating models of ISCCs in posterior mandible were fabricated. Twelve clinical simulating models consisted of three CPPs, two cement thickness (30 and 60 microns) and two load directions (axial and oblique) were investigated. The finite element analysis was performed, and the stress of implant, prosthesis and periodontal ligament, strain of the bone, and displacement of teeth were recorded and analyzed.
Results: All clinical simulating models, oblique loads can cause more significant biomechanical performance compared to axial loads. The CPPs design significantly influences the biomechanical performance of ISCCs. It found that the mesial CPP (MCPP) experienced lower levels of bone strains compared to regular CPP (RCPP) and distal CPP (DCPP). The cement thickness is generally considered to have a minor impact compared to other factors.

* Corresponding author. Faculty of Dentistry, Thammasat University, 99 Moo 18, Phaholyothin Road, Khlong Luang District, Pathumthani 12120, Thailand.
E-mail address: isamroeng@gmail.com (S. Inglam).

https://doi.org/10.1016/j.jds.2025.11.009

Conclusion: In biomechanical point of view, the CPPs design influences the biomechanical performance of ISCCs. The MCPP is considered biomechanically more advantageous especially in terms of reducing strain on the surrounding bone. Clinicians should carefully consider this factor to ensure optimal biomechanical performance and minimize the risk of biomechanical complications.

Introduction

In certain clinical situations, particularly for elderly patients, implant-supported cantilever crowns (ISCCs) can be a viable alternative to avoid additional, potentially risky surgical procedures. The ISCCs can offer a less invasive treatment option, reducing the need for more complex surgeries.[1] However, many biomechanical factors have been found to influence the long term success of implant treatment, including the prosthetic superstructure design, as well as the occlusion type and masticatory forces of patient.[2–4] Numerous studies have shown that ISCCs can induce excessive stress concentrations in the surrounding bone.[4–7] In clinical practices, mesial cantilevers are generally preferred as they distribute forces more favorably.[8] The optimal prosthesis design for a partial edentulous can vary significantly based on individual needs. Factors like aesthetics, comfort and ease of cleaning can all influence the final prosthesis design.[9] In ISCCs prosthesis, the relationship of cantilever design and excessive occlusal-loading force is still controversies. The biomechanics of implant systems are crucial for the long-term success of dental implant therapy.[10] Inappropriate loads applied to cantilevers have also produced additional stresses leading to surrounding bone loss and implant structure failure.[11,12]

In the ISCCs design, the connector, areas where different parts of the cantilever and abutment are joined which can be positioned mesially (towards the front) or distally (towards the back). The connector position placing (CPPs) is crucial and can be adjusted to optimize the biomechanics. This is because the connector position affects the distribution of forces and the necessary space for the prosthesis. In clinical practice, ISCCs replacing a 1st molar and 2nd premolar can be a viable connector position placing, particularly when the connector is placed more mesially or distally relative to the 2nd premolar width, it necessitates a wider or narrower 1st molar to accommodate the prosthesis. Theoretically, geometric discontinuities like connectors can cause stress concentrations. These features disrupt the smooth flow of stress, leading to localized stress intensification, which can weaken structures and potentially lead to failure.[13] Changing the CPPs can alter biomechanical performance of ISCCs system. Therefore, CPPs may important to decision for overall success of the implant therapy. According to the type of retention method, cement retained techniques are mostly used because of their benefits of improved aesthetics, passive fit, and simple procedure.[14] Cement thicknesses widely reported by different authors range from 20 to 40 microns.[15] Ceddia et al. reported that the optimal cement thickness ranges between 40 and 60 microns.[16] The aim of the current study was to investigate the biomechanical performance of ISCCs with different CPPs and cement thickness under axial and oblique loading conditions, analyzed by finite element analysis (FEA).

Materials and methods

Finite element model of the implant-supported cantilever crown system

To create clinical simulating study models of ISCCs (Fig. 1A), The 3-D models of mandibular bone and prosthesis (crown with cantilever) were created from scanned data of an artificial dental study model. They were developed using Meshmixer software (Autodesk Inc., San Francisco, CA, USA). We assemble 3-D models incorporating the implant, cement layer, abutment, prosthesis, adjacent teeth with periodontal ligament (PDL) (2nd molar and 1st

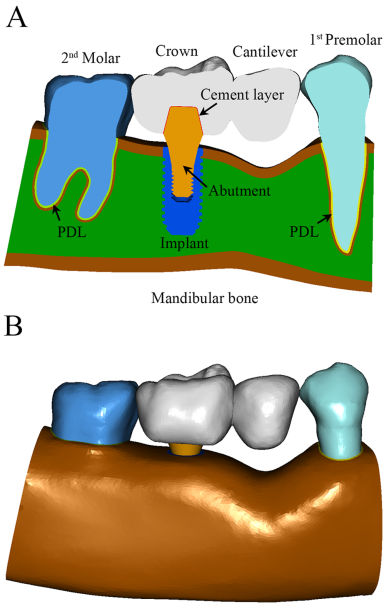

Figure 1 (A) Clinical simulating study model of ISCCs system and surrounding structure. (B) The 3-D models of clinical simulating study model. PDL, periodontal ligament.

premolar), and mandibular bone (Fig. 1B). This study is taking a different CPPs, keeping the overall edentulous space and cantilever length the same. The design of the ISCCs prosthesis, specifically the mesio-distal dimension of the connector between the 2nd premolar (cantilever) and 1st molar (crown), influences the width of the molar needed. A mesial CPP (MCPP) leads to a wider molar, while a distal CPP (DCPP) results in a narrower molar. For clinical simulating study models, the mesio-distal width of a crown can be varied by increasing or decreasing its width by 10 % from regular CPP (RCPP) for distal and mesial designs respectively. According to the clinical scenario of this study, a partial edentulous spacing of a fixed length of 18.9876 mm which corresponded to mean values of 2nd mandibular premolar and 1st mandibular molar crown widths.[17] This study compared the biomechanics with different CPPs, while keeping the total cantilever length at 12.9274 mm (Fig. 2A). This could involve the regular position (RCPP) and moving the connector closer to (DCPP) or further away from (MCPP) the implant. Twelve clinical simulating models consisted of three CPPs (RCPP, MCPP, DCPP), two cement thicknesses (30, and 60 microns) and two load directions (axial and oblique) were investigated (Table 1). These models were used in FEA to simulate how the ISCCs systems and surrounding structures respond to forces in a simulated clinical scenario. The FEA models were created using Patran mesh generation software (MSC Software Corporation, Newport Beach, CA, USA) (Fig. 2B). The mechanical property in this study assumed linearly elastic and isotropic as shown in Table 2.[18–23]

Loading conditions

The applied load was 37 % of the maximum bite force as shown in Table 3.[24,25] The axial and oblique load were applied on the center of occlusal surface. The load

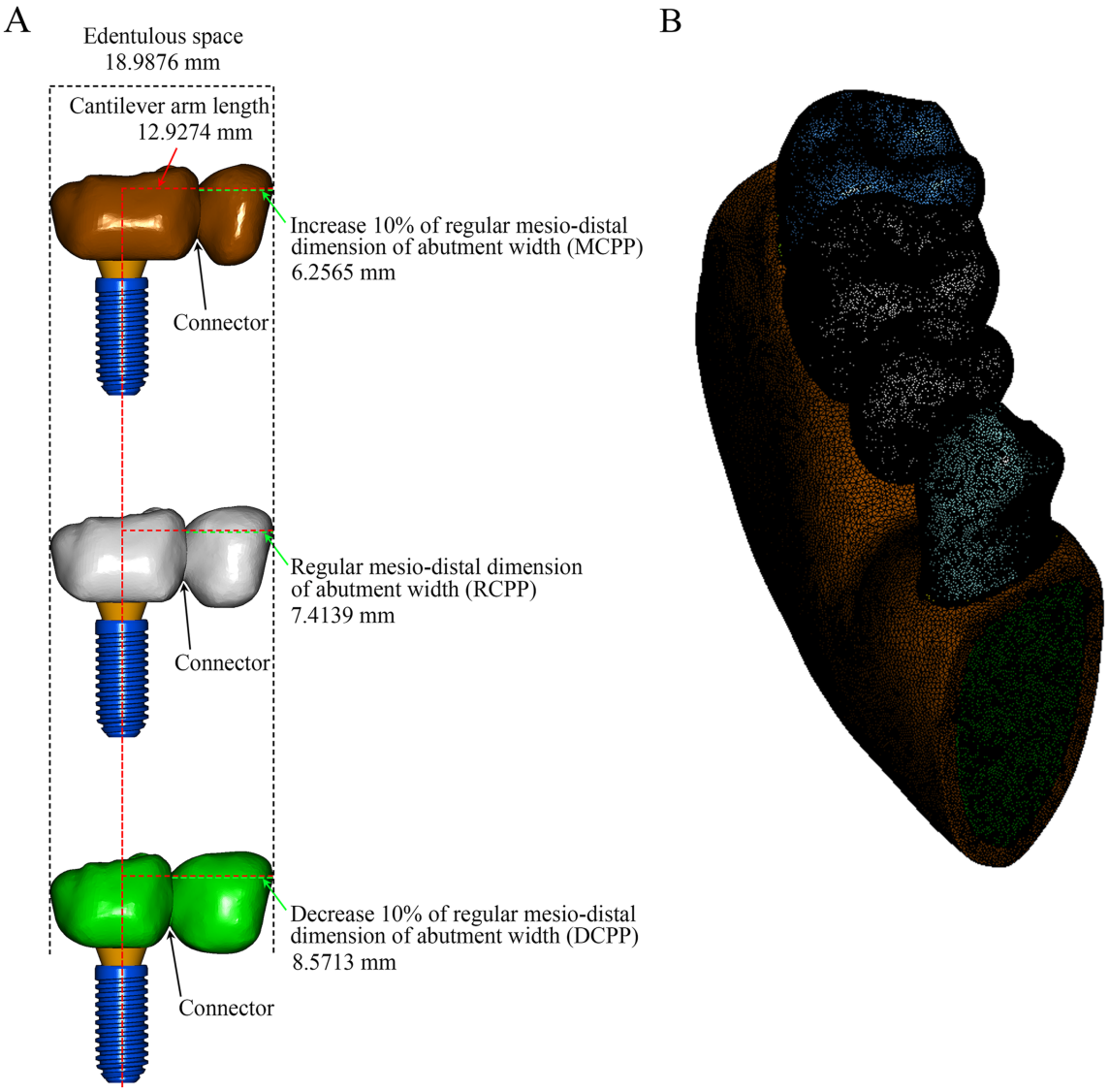

Figure 2 (A) Buccal aspect of MCPP, RCPP and DCPP of ISCC systems. (B) Mesh of clinical simulating study models for FEA. DCPP, distal connector position placing; MCPP, mesial connector position placing; mm, millimeter; RCPP, regular connector position placing.

Table 1 Clinical simulating study models of ISCCs.

Clinical simulating study models	Connector position	Cement thickness (microns)	Load direction
RCPP-30-A	Regular	30	Axial
RCPP-30-O	Regular	30	Oblique
RCPP-60-A	Regular	60	Axial
RCPP-60-O	Regular	60	Oblique
MCPP-30-A	Mesial	30	Axial
MCPP-30-O	Mesial	30	Oblique
MCPP-60-A	Mesial	60	Axial
MCPP-60-O	Mesial	60	Oblique
DCPP-30-A	Distal	30	Axial
DCPP-30-O	Distal	30	Oblique
DCPP-60-A	Distal	60	Axial
DCPP-60-O	Distal	60	Oblique

DCPP-30-A, distal connector position placing with cement thickness 30 microns and axial load; DCPP-30-O, distal connector position placing with cement thickness 30 microns and oblique load; DCPP-60-A, distal connector position placing with cement thickness 60 microns and axial load; DCPP-60-O, distal connector position placing with cement thickness 60 microns and oblique load; MCPP-30-A, mesial connector position placing with cement thickness 30 microns and axial load; MCPP-30-O, mesial connector position placing with cement thickness 30 microns and oblique load; MCPP-60-A, mesial connector position placing with cement thickness 60 microns and axial load; MCPP-60-O, mesial connector position placing with cement thickness 60 microns and oblique load; RCPP-30-A, regular connector position placing with cement thickness 30 microns and axial load; RCPP-30-O, regular connector position placing with cement thickness 30 microns and oblique load; RCPP-60-A, regular connector position placing with cement thickness 60 microns and axial load; RCPP-60-O, regular connector position placing with cement thickness 60 microns and oblique load.

Table 2 Mechanical properties of material.[18–23]

Materials	Young's modulus (MPa)	Poisson's ratio
Natural tooth	19,600	0.3
Zirconia	210,000	0.3
Resin cement	8,300	0.35
Titanium alloy	110,000	0.28
PDL	50	0.49
Cortical bone	13,700	0.3
Cancellous bone	1,370	0.3

MPa, mega Pascal; PDL, periodontal ligament.

direction was from the lingual side to buccal side as shown in Fig. 3. All finite element analyses were performed in Marc Mentat software (MSC Software Corporation, Newport Beach, CA, USA). The element type used in the analysis was a four-noded tetrahedral, with the number of elements

Table 3 Load used in each tooth, cantilever, and crown.[24,25]

Tooth and prosthetic components	Axial load (N)	Oblique load (N)
1st premolar	85.41	85.41
2nd premolar (cantilever)	98.09	98.09
1st molar (crown on implant abutment)	105.09	105.09
2nd molar	100.63	100.63

N, Newton.

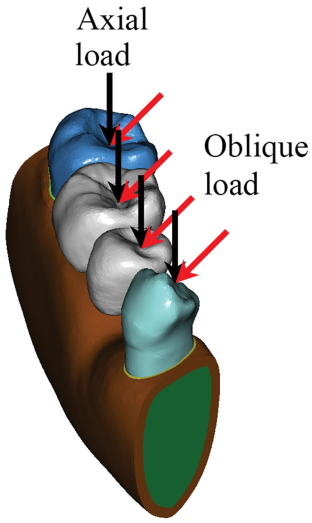

Figure 3 Axial and oblique load directions applied on the center of occlusal surface.

ranging from 1,433,584 to 1,454,053 depending on the model components. The convergence tested showed that von Mises stress in the implant converge when the number of elements reach 1,400,000 as shown in Fig. 4.

Results

The principal stress of prosthesis and von Mises stress of implant

According to the CPPs design, the result of this study demonstrated that the DCPPs of axial loads of both cement thickness models (DCPP-30-A and DCPP-60-A) were cause approximately three times more than the maximum principal stress of prosthesis of the MCPPs and the RCPP in the set of models which the same cement thickness (DCPP-30-A with MCPP-30-A and RCPP-30-A, DCPP-60-A with MCPP-60-A and RCPP-60-A) (Table 4). The highest principal stress was DCPP-30-A. When considering the cement thickness, the result of this study showed that the different cement thicknesses had no significant impact on the stress experienced by the prosthesis under both axial and oblique loading. In all clinical simulating models, stress tends to concentrate at connectors. This stress concentration can lead to higher stress values compared to other parts of the

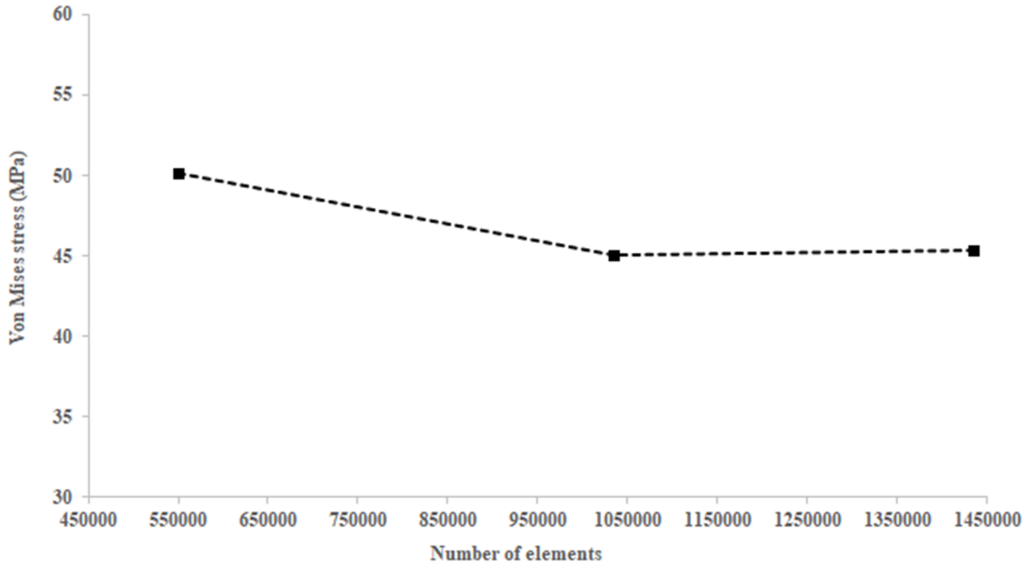

Figure 4 Convergence test of the von Mises stress in the implant. MPa, mega Pascal.

Table 4 Maximum principal stress in prosthesis and maximum microstrains in surrounding bone.

Clinical simulating models	Maximum principle stress in prosthesis (MPa)	Maximum microstrains in surrounding bone
RCPP-30-A	68.23	1505.31
RCPP-30-O	140.93	6047.4
RCPP-60-A	66.51	1493.11
RCPP-60-O	125.21	6059.49
MCPP-30-A	64.83	1556.53
MCPP-30-O	122.95	5536.92
MCPP-60-A	59.75	1551.85
MCPP-60-O	111.1	5535.57
DCPP-30-A	181.80	1322.34
DCPP-30-O	95.15	6135.24
DCPP-60-A	167.19	1321.54
DCPP-60-O	90.24	6147.74

DCPP-30-A, distal connector position placing with cement thickness 30 microns and axial load; DCPP-30-O, distal connector position placing with cement thickness 30 microns and oblique load; DCPP-60-A, distal connector position placing with cement thickness 60 microns and axial load; DCPP-60-O, distal connector position placing with cement thickness 60 microns and oblique load; MCPP-30-A, mesial connector position placing with cement thickness 30 microns and axial load; MCPP-30-O, mesial connector position placing with cement thickness 30 microns and oblique load; MCPP-60-A, mesial connector position placing with cement thickness 60 microns and axial load; MCPP-60-O, mesial connector position placing with cement thickness 60 microns and oblique load; MPa, mega Pascal; RCPP-30-A, regular connector position placing with cement thickness 30 microns and axial load; RCPP-30-O, regular connector position placing with cement thickness 30 microns and oblique load; RCPP-60-A, regular connector position placing with cement thickness 60 microns and axial load; RCPP-60-O, regular connector position placing with cement thickness 60 microns and oblique load.

prosthesis (Fig. 5A). Considering stress on implant, the result indicated that the higher stress concentration located on cervical region of all simulating models. Under axial loading, the stress was predominantly directed towards the mesial side of the implant. However, oblique loading resulted in increased stress on the buccal side (Fig. 5B).

The microstrains in surrounding bone

A DCPP resulted in lower levels of microstrains compared to other designs under axial load while an MCPP resulted in lower levels of microstrains compared to other designs under oblique load (Table 4). Considering strain distribution pattern, in all simulating models, the high strain for axial load occurred on marginal of the surrounding bone. When subjected to oblique load, the highest strain shifted to the buccal site of the marginal bone. Some of strain distribution pattern were shown in Fig. 6.

The displacement of teeth and von Mises stress of periodontal ligament

The study indicates that teeth adjacent to ISCCs experience displacement when subjected to loads, with the 1st premolar exhibiting greater displacement than the 2nd molar. Furthermore, oblique loads cause more displacement than axial loads in both adjacent teeth (Fig. 7). Considering the affected to PDL, the 1st premolar PDL also experiences higher von Mises stress compared to the 2nd molar PDL under both load directions, and oblique loads tend to generate greater maximum von Mises stress within the PDL. However, the von Mises stress distribution pattern remained consistent across all teeth (Figs. 7 and 8).

Discussion

In some clinical situations, ISCCs can minimize the need of multiple surgical for additional procedures. These options

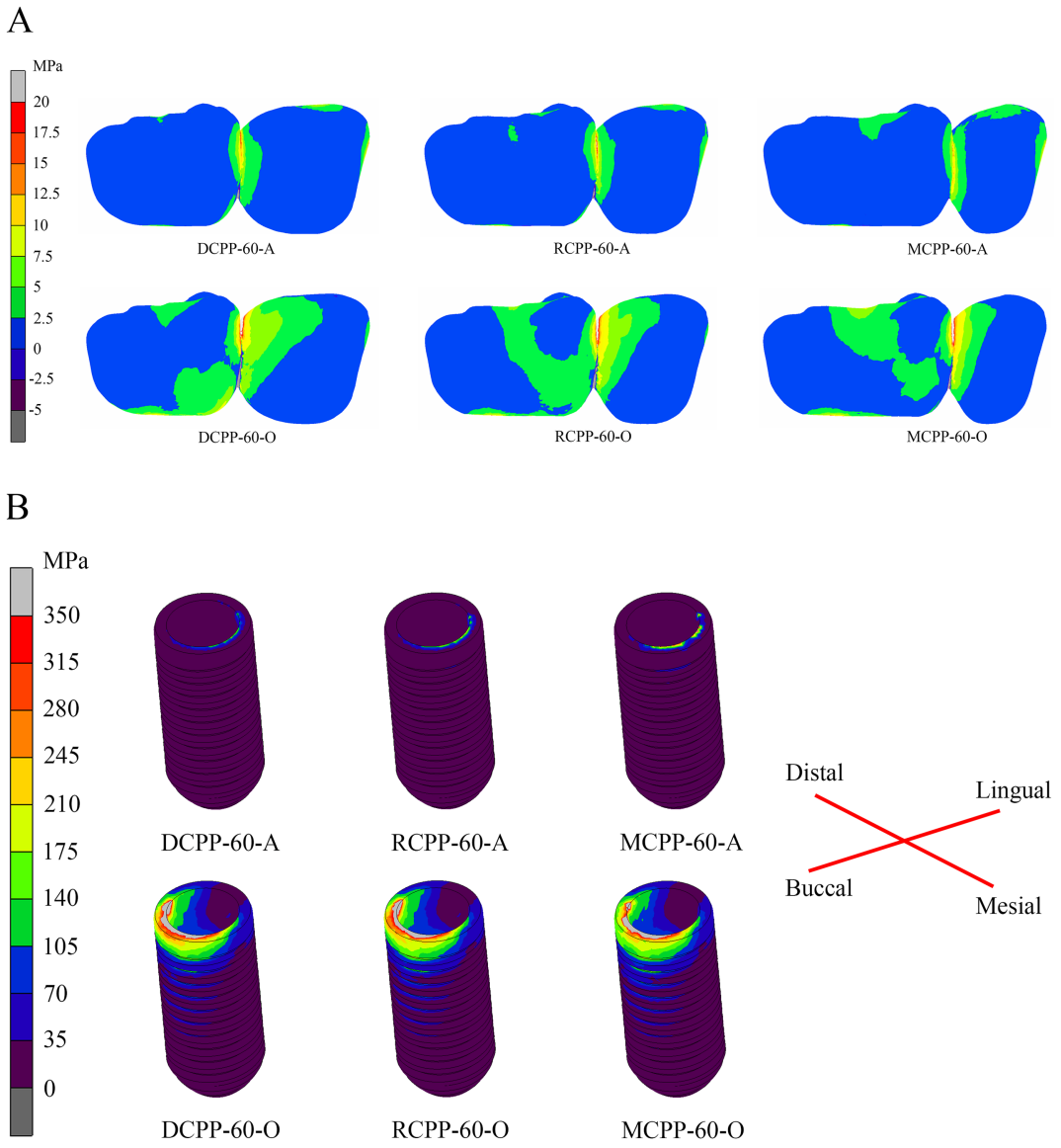

Figure 5 (A) Principal stress distribution pattern of prosthesis of axial and oblique load. (B) Von Mises stress distribution pattern of implant. DCPP-60-A, distal connector position placing with cement thickness 60 microns and axial load; DCPP-60-O, distal connector position placing with cement thickness 60 microns and oblique load; MCPP-60-A, mesial connector position placing with cement thickness 60 microns and axial load; MCPP-60-O, mesial connector position placing with cement thickness 60 microns and oblique load; MPa, mega Pascal; RCPP-60-A, regular connector position placing with cement thickness 60 microns and axial load; RCPP-60-O, regular connector position placing with cement thickness 60 microns and oblique load.

are widely used in prosthetic rehabilitation, which involves replacing missing teeth with prostheses to restore function, aesthetics, and oral health.[1] For successful ISCCs, careful consideration of biomechanical factors is essential.[26–30] These factors include the prosthesis design, cement thickness, and load direction, which all influence the long-term success of the treatment.[15,31] Analyzing the biomechanical performance of the chosen design of this study is crucial for predicting its long-term stability and preventing potential complications. Investigating of the biomechanical performance involves evaluating how the prosthetic components, surrounding bone, PDL of adjacent teeth will respond to various influencing factors. This can be done using finite element method to simulate and identify potential strength and weaknesses in the clinical scenarios.[31,32]

The result showed load direction had a major effect on the biomechanical performance of ISCCs. For the stress distribution pattern of prosthesis, oblique loads tend to concentrate stress at the connectors more than axial loads. This is a common finding in finite element analysis studies of implant-supported prostheses.[32] The oblique load creates a bending and twisting moment, which is a rotational force leads to higher stress concentrations at the point of the connector because it's trying to twist the prosthesis. This concentration is due to the abrupt changes in geometry at this location, which can lead to higher stress values

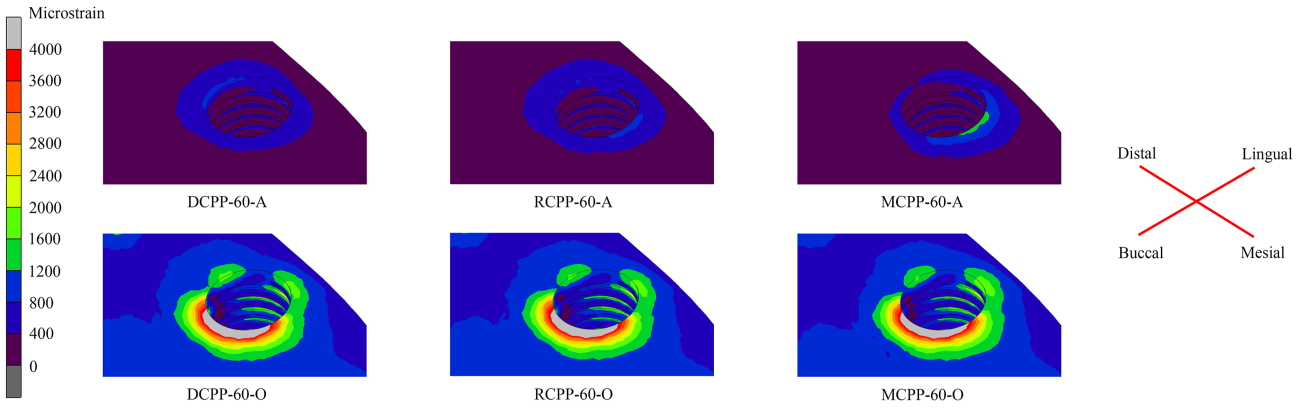

Figure 6 The strain distribution pattern in surrounding bone. DCPP-60-A, distal connector position placing with cement thickness 60 microns and axial load; DCPP-60-O, distal connector position placing with cement thickness 60 microns and oblique load; MCPP-60-A, mesial connector position placing with cement thickness 60 microns and axial load; MCPP-60-O, mesial connector position placing with cement thickness 60 microns and oblique load; RCPP-60-A, regular connector position placing with cement thickness 60 microns and axial load; RCPP-60-O, regular connector position placing with cement thickness 60 microns and oblique load.

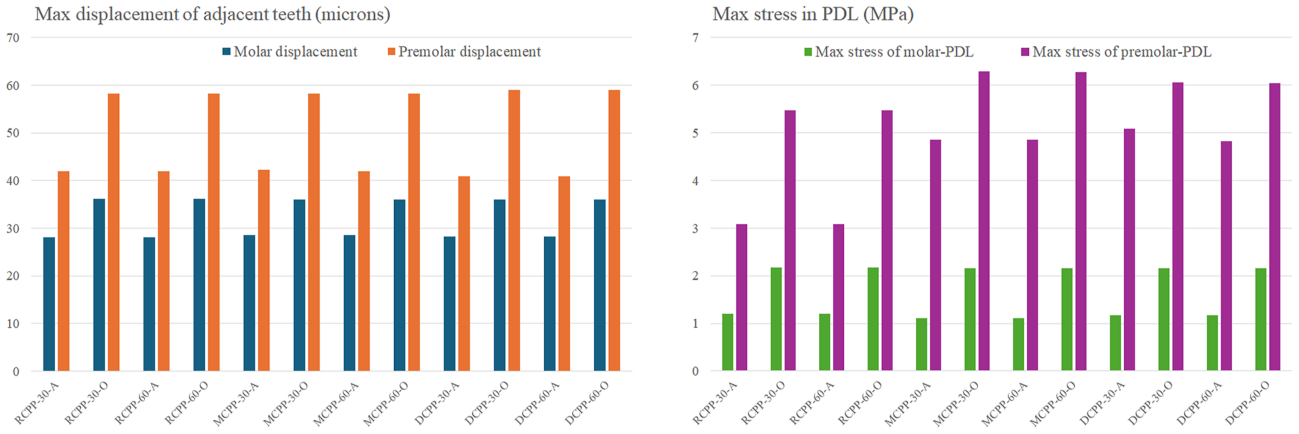

Figure 7 Maximum displacement of teeth and maximum von Mises stress of PDL. DCPP-30-A, distal connector position placing with cement thickness 30 microns and axial load; DCPP-30-O, distal connector position placing with cement thickness 30 microns and oblique load; DCPP-60-A, distal connector position placing with cement thickness 60 microns and axial load; DCPP-60-O, distal connector position placing with cement thickness 60 microns and oblique load; Max, maximum; MCPP-30-A, mesial connector position placing with cement thickness 30 microns and axial load; MCPP-30-O, mesial connector position placing with cement thickness 30 microns and oblique load; MCPP-60-A, mesial connector position placing with cement thickness 60 microns and axial load; MCPP-60-O, mesial connector position placing with cement thickness 60 microns and oblique load; MPa, mega Pascal; PDL, periodontal ligament; RCPP-30-A, regular connector position placing with cement thickness 30 microns and axial load; RCPP-30-O, regular connector position placing with cement thickness 30 microns and oblique load; RCPP-60-A, regular connector position placing with cement thickness 60 microns and axial load; RCPP-60-O, regular connector position placing with cement thickness 60 microns and oblique load.

than in other parts of the prosthesis. The analysis of stress distribution patterns in the implants revealed that higher stress concentrations are primarily located in the cervical region across all clinical models. These findings aligned with previous research which suggest that the cervical area is a critical region, and the load direction significantly influences stress distribution. Structures with stress concentrations are more susceptible to damage from external forces.[33] The results of this study associated with previous research, it indicated that clinicians often consider the direction of occlusal forces when planning ISCCs to minimize stress and optimize long-term success.[32]

Excessive occlusal forces, particularly when coupled with cantilever designs in dental implants, can lead to increased stress and bending moments, potentially compromising the long-term success of the implant.[34,35] The resulting of leverage force might cause the high concentration of stress in the implant system and surrounding bone.[6] Therefore, optimal prosthetic design should strive to minimize stress on the implant and surrounding bone while also considering the patient's functional and aesthetic needs. The biomechanics of ISCCs involve understanding how loads are distributed, especially when a part of the prosthesis extends beyond the supporting implants (which

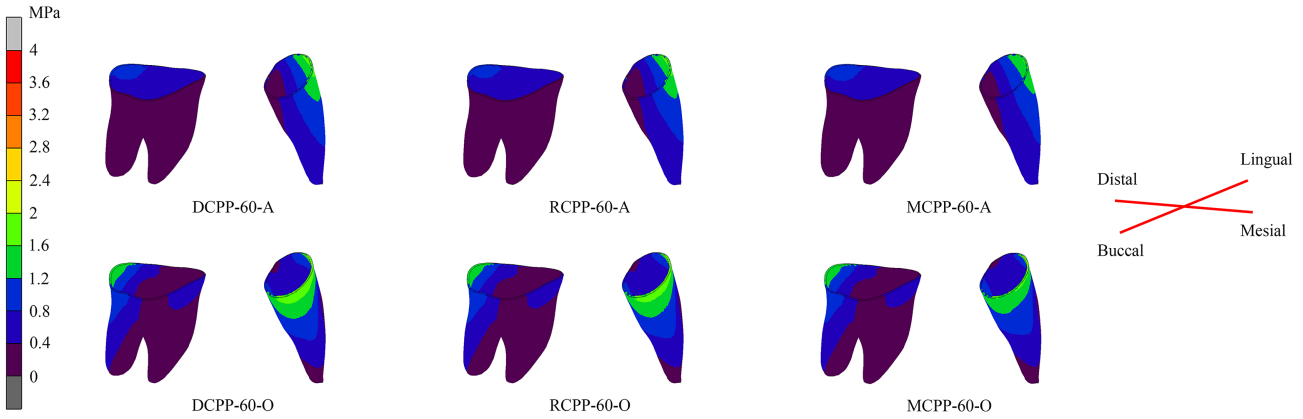

Figure 8 Von Mises stress distribution pattern in PDL. DCPP-60-A, distal connector position placing with cement thickness 60 microns and axial load; DCPP-60-O, distal connector position placing with cement thickness 60 microns and oblique load; MCPP-60-A, mesial connector position placing with cement thickness 60 microns and axial load; MCPP-60-O, mesial connector position placing with cement thickness 60 microns and oblique load; MPa, mega Pascal; RCPP-60-A, regular connector position placing with cement thickness 60 microns and axial load; RCPP-60-O, regular connector position placing with cement thickness 60 microns and oblique load.

behave like a class I lever), is essential for minimizing stress and preventing bone loss or implant failure.[36]

Previous study usually finding the influence of cantilever arm length on the biomechanical performance.[2,6,37] In this study, the cantilever arm length was kept constant. The objective was to investigate the effects of force direction and connector design at various positions along the cantilever arm. The presence of a connector acts as an additional minor fulcrum at positions between the mesial end of the cantilever and the original fulcrum (the center of implant). The results of this study demonstrated that the CPPs design influenced the biomechanical performance of ISCCs. The result demonstrated that under axial load condition, DCPP exhibited better biomechanical performance than RCPP and MCPP in the term of surrounding bone strains. This is because an axial load primarily induces bending movement; a connector located closer to the implant results in a shorter distance between the original fulcrum and the new one as in DCPP, leading to reduced bending movement. Consequently, this results in better biomechanical performance than RCPP and MCPP, whose connectors are positioned farther from the implant, respectively. However, under axial load, the maximum microstrain values in the surrounding bone of all connector positions models (RCPP, MCPP and DCPP) did not exceed the bone resorption threshold of 4,000 microstrains, as stated in Frost's mechanostat.[38]

Clinically, masticatory forces are rarely purely axial because normal chewing involves a combination of muscle actions that create a chewing cycle. Therefore, the oblique loading is the predominant direction of force during chewing. The study revealed under oblique loading, models with the connector positioned more mesially (MCPP) demonstrated improved biomechanical performance compared to RCPP and DCPP. This is because when they are oblique, they create significant bending and torsional forces on the prosthesis. These oblique forces tend to concentrate stress around the implant's neck and at the bone-implant interface. Placing a connector more mesially under oblique loading can improve biomechanical performance by helping to counteract the bending and torsional forces that occur with oblique forces.[39] This is because it can help to more favorably distribute stress away from the implant's neck area, which is a common point of high stress concentration under oblique loading, and toward the bone, which can bear the stress more effectively.

The current study's findings aligned with other research indicating that cement thickness has a less significant impact on biomechanical performance of ISCCs compared to other factors.[17,26,35] Although the biomechanical performance of ISCCs is influenced by several factors, but cement thickness is generally considered to have a minor impact compared to other variables. In this study, the initial cement thickness was chosen at 30 microns instead of 20 microns as suggested by Squier et al.[15] because of the need for balancing the clinical benefits of thin cement layers for better restoration fit with the stress-absorbing potential of thicker layers. While thinner layers are good for fit, thicker layers can absorb more stress, which may be beneficial for the implant–bone interface. This indicate that a slightly thicker space, up to 60 microns, may be optimal for reducing stress in some implant situations.[16] Another study suggested 25–35 microns for optimal bond strength.[40] Therefore this study was chosen the cement thickness range from 30 to 60 microns for clinical simulating study models. While cement thickness does play a role in the overall fit and seal of the restoration, its effect on biomechanics less significant than factors like load directions and CPPs.Therefore, clinicians should prioritize these more influential factors when designing prosthetic components to ensure long-term stability and success.

This study differed from the previous studies in the simulated PDL to analyze the biomechanical performance of ISCCs. The PDL is a soft tissue that suspends the tooth within the alveolar bone and absorb the stress. While the PDL is flexible, it has a limited capacity for displacement. The maximum displacement of a tooth within the PDL is typically in the range of 73.8 microns.[36,41,42] Displacement

is influenced by factors such as the force applied, individual tooth and bone characteristics. The result of this study indicates that the 1st premolar showed more displacement than the 2nd molar under the same loading conditions. This suggests that the 1st premolar might be more susceptible to displacement due to its structural characteristics (e.g., root length, root shape, bone density) or its position within the simulated jaw. Considering load direction, the oblique load produced greater displacement than the axial load. This is likely because oblique forces can generate rotational and shear forces within the tooth and surrounding structures, leading to increased displacement. The findings were based on clinical simulating model, which implies the use of FEA. These models were used to simulate the behavior of teeth and surrounding tissues under various loading conditions. Furthermore, more clinical studies are necessary to determine the biomechanical performance by this type of prosthesis, to produce a more complete analysis of the longevity of rehabilitations with ISCCs.

Although the FEA is widely used in biomechanical investigation of dental implant but it has some limitation include simplified assumptions about perfect osseointegration and FEA models often assume bone as isotropic and homogenous. The FEA often simplify chewing and other dynamic forces to static. Therefore, the clinical application must be considering and clinical study should be in further study for validation.

However, in biomechanical point of view and limitation of this study, it can be concluded that ISCCs in the posterior mandible is a viable treatment option. The CPPs design on the prosthesis of implant supported crown and load directions has a biomechanical impact. Clinicians should carefully consider when designing CPPs on prosthesis design. The load direction is a combination factors which emphasize in biomechanical consideration. In cases of oblique loading which represents the predominant direction of normal masticatory forces, placing the connector position mesially can help biomechanical performance more favorably.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

Acknowledgments

The authors would like to thank the Thammasat University Research Unit in Dental Biomechanics, Thammasat University, for providing funds and assistance for this work.

References

1. Hälg GA, Schmid J, Hämmerle CH. Bone level changes at implants supporting crowns or fixed partial dentures with or without cantilevers. *Clin Oral Implants Res* 2008;19:983—90.
2. de Souza Batista VE, Verri FR, Almeida DA, Santiago Junior JF, Lemos CA, Pellizzer EP. Finite element analysis of implant-supported prosthesis with pontic and cantilever in the posterior maxilla. *Comput Methods Biomech Biomed Eng* 2017;20:663—70.
3. Shen YW, Huang HL, Hsu JT, Fuh LJ. Effects of diameters of implant and abutment screw on stress distribution within dental implant and alveolar bone: a three-dimensional finite element analysis. *J Dent Sci* 2024;19:1126—34.
4. Sakar D, Guncu MB, Arikan H, et al. Effect of different implant locations and abutment types on stress and strain distribution under non-axial loading: a 3-dimensional finite element analysis. *J Dent Sci* 2024;19:607—13.
5. Kunavisarut C, Lang LA, Stoner BR, Felton DA. Finite element analysis on dental implant-supported prostheses without passive fit. *J Prosthodont* 2002;11:30—40.
6. Huang LS, Huang YC, Yuan C, Ding SJ, Yan M. Biomechanical evaluation of bridge span with three implant abutment designs and two connectors for tooth-implant supported prosthesis: a finite element analysis. *J Dent Sci* 2023;18:248—63.
7. Huang YC, Ding SJ, Yuan C, Yan M. Biomechanical analysis of rigid and non-rigid connection with implant abutment designs for tooth-implant supported prosthesis: a finite element analysis. *J Dent Sci* 2022;17:490—9.
8. Aglietta M, Siciliano VI, Zwahlen M, et al. A systematic review of the survival and complication rates of implant supported fixed dental prostheses with cantilever extensions after an observation period of at least 5 years. *Clin Oral Implants Res* 2009;20:441—51.
9. Borges GA, Barbin T, Dini C, et al. Patient-reported outcome measures and clinical assessment of implant-supported overdentures and fixed prostheses in mandibular edentulous patients: a systematic review and meta-analysis. *J Prosthet Dent* 2022;127:565—77.
10. Jin ZH, Peng MD, Li Q. The effect of implant neck microthread design on stress distribution of peri-implant bone with different level: a finite element analysis. *J Dent Sci* 2020;15:466—71.
11. White SN, Caputo AA, Anderkvist T. Effect of cantilever length on stress transfer by implant-supported prostheses. *J Prosthet Dent* 1994;71:493—9.
12. Osier JF. Biomechanical load analysis of cantilevered implant systems. *J Oral Implantol* 1991;17:40—7.
13. Chen YY, Kuan CL, Wang YB. Implant occlusion: biomechanical considerations for implant-supported prostheses. *J Dent Sci* 2008;3:65—74.
14. Ma S, Fenton A. Screw- versus cement-retained implant prostheses: a systematic review of prosthodontic maintenance and complications. *Int J Prosthodont (IJP)* 2015;28:127—45.
15. Squier RS, Agar JR, Duncan JP, Taylor TD. Retentiveness of dental cements used with metallic implant components. *Int J Oral Maxillofac Implants* 2001;16:793—8.
16. Ceddia M, Romasco T, Comuzzi L, et al. The influence of cement thickness within the cap on stress distribution for dental implants. *J Funct Biomater* 2024;15:199.
17. Song JW, Leesungbok R, Park SJ, Chang SH, Ahn SJ, Lee SW. Analysis of crown size and morphology, and gingival shape in the maxillary anterior dentition in korean young adults. *J Adv Prosthodont* 2017;9:315—20.
18. Gomez JP, Peña FM, Martínez V, Giraldo DC, Cardona CI. Initial force systems during bodily tooth movement with plastic aligners and composite attachments: a three-dimensional finite element analysis. *Angle Orthod* 2015;85:454—60.
19. De Jager N, de Kler M, van der Zel JM. The influence of different core material on the FEA-determined stress distribution in dental crowns. *Dent Mater* 2006;22:234—42.
20. Rees JS, Jacobsen PH. Elastic modulus of the periodontal ligament. *Biomaterials* 1997;18:995—9.
21. Daas M, Dubois G, Bonnet AS, Lipinski P, Rignon-Bret C. A complete finite element model of a mandibular implant-retained overdenture with two implants: comparison

between rigid and resilient attachment configurations. *Med Eng Phys* 2008;30:218—25.
22. Liu B, Lu C, Wu Y, Zhang X, Arola D, Zhang D. The effects of adhesive type and thickness on stress distribution in molars restored with all-ceramic crowns. *J Prosthodont* 2011;20: 35—44.
23. Soncini M, Pietrabissa R, Natali A, Pavan P, Williams K. Testing the reliability of dental implant devices. In: Natali A, ed. *Dental biomechanics*. London: Taylor and Francis, 2003:111—31.
24. Ferrario VF, Sforza C, Serrao G, Dellavia C, Tartaglia GM. Single tooth bite forces in healthy young adults. *J Oral Rehabil* 2004; 31:18—22.
25. Imanishi A, Nakamura T, Ohyama T, Nakamura T. 3-D finite element analysis of all-ceramic posterior crowns. *J Oral Rehabil* 2003;30:818—22.
26. Durkan R, Oyar P, Deste G. Effects of cantilever length and implant inclination on the stress distribution of mandibular prosthetic restorations constructed from monolithic zirconia ceramic. *Int J Oral Maxillofac Implants* 2020;35:121—9.
27. Sadek HS, Anany NM, El-Anwar MI, et al. Biomechanical behavior of cantilevered 3-unit implant-supported prostheses made of pekk and monolithic zirconia: a finite element study. *J Mech Behav Biomed Mater* 2025;163:106872.
28. Tashkandi EA, Lang BR, Edge MJ. Analysis of strain at selected bone sites of a cantilevered implant-supported prosthesis. *J Prosthet Dent* 1996;76:158—64.
29. Ceresuela P, Montero J. Biomechanical factors in the prognosis of implants: a clinical study. *Prosthesis* 2024;6:896—912.
30. Moraschini V, Poubel LA, Ferreira VF, Barboza Edos S. Evaluation of survival and success rates of dental implants reported in longitudinal studies with a follow-up period of at least 10 years: a systematic review. *Int J Oral Maxillofac Surg* 2015;44: 377—88.
31. Chen Y-Y, Kuan C-L, Wang Y-B. Implant occlusion: biomechanical considerations for implant-supported prostheses. *J Dent Sci* 2008;3:65—74.
32. Pellizzer EP, Falcón-Antenucci RM, de Carvalho PS, et al. Influence of implant angulation with different crowns on stress distribution. *J Craniofac Surg* 2011;22:434—7.
33. Souza AF, De Zoppa ALdV. Stress riser in orthopedics. *Glob J Orthop Res* 2022;1:8—10.
34. Himmel R, Pilo R, Assif D, Aviv I. The cantilever fixed partial denture–a literature review. *J Prosthet Dent* 1992; 67:484—7.
35. Greenstein G, Cavallaro Jr J. Cantilevers extending from unilateral implant-supported fixed prostheses: a review of the literature and presentation of practical guidelines. *J Am Dent Assoc* 2010;141:1221—30.
36. Jansen van Vuuren L, Jansen van Vuuren WA, Broadbent JM, Duncan WJ, Waddell JN. Measurement of tooth displacement. *J Mech Behav Biomed Mater* 2023;146:106059.
37. Gallucci GO, Doughtie CB, Hwang JW, Fiorellini JP, Weber H-P. Five-year results of fixed implant-supported rehabilitations with distal cantilevers for the edentulous mandible. *Clin Oral Implants Res* 2009;20:601—7.
38. Frost HM. Bone "mass" and the "mechanostat": a proposal. *Anat Rec* 1987;219:1—9.
39. Ceddia M, Marchioli G, Romasco T, et al. Effect of crestal position on bone-implant stress interface of three-implant splinted prostheses: a finite element analysis. *Materials* 2025;18.
40. Aker Sagen M, Dahl JE, Matinlinna JP, Tibballs JE, Rønold HJ. The influence of the resin-based cement layer on ceramic-dentin bond strength. *Eur J Oral Sci* 2021;129:e12791.
41. Fongsamootr T, Suttakul P. Effect of periodontal ligament on stress distribution and displacement of tooth and bone structure using finite element simulation. *Eng J* 2015;19: 99—108.
42. Geramy A, Adibrad M, Sahabi M. The effects of splinting periodontally compromised removable partial denture abutments on bone stresses: a three-dimensional finite element study. *J Dent Sci* 2010;5:1—7.