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The optimal design and three-dimensional finite element analysis of CAD/CAM integrated roach attachment

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ABSTRACT

Objectives: To investigate the effect of different designs of movable parts and prosthetic materials on the stress distribution of supporting tissues in mandibular free end dentition defects using three-dimensional finite element analysis of digital Roach attachments.
Material and methods: A 3D model of a patient with Kennedy class I mandibular edentulous conditions was generated, and twelve prosthesis models were applied, combining two designs of removable parts and six types of CAD/CAM restorative materials with different elastic modulus (conventional zirconia, ultra-translucent zirconia, Polyetheretherketone (PEEK), Lithium disilicate, Nanoceramic resin, and resin composite (Paradigm MZ100, 3 M ESPE)). The stress distribution of abutment periodontal ligament, edentulousmucosa, and junction of attachment were analyzed using finite element analysis.
Results: The stress value of the buccal neck of the periodontal ligament and the maximum compressive stress of the distal periodontal ligament of the design with clasp arms were higher than those without clasp arms, while the stress on the junction of attachment and the displacement of the mucosa in the edentulous area were smaller. Restorative materials with high elastic modulus, such as conventional zirconia and ultra-translucent zirconia, are recommended to be used as the fixed part of Roach attachment.
Conclusion: CAD/CAM Roach attachments with clasp arms are recommended for the protection of mucosal soft tissue. Restorative materials with high elastic modulus, such as conventional zirconia and ultra-translucent zirconia, are recommended as the fixed part of Roach attachment for patients with free end defect of mandibular dentition.
Clinical significance: This study provides references for the design with clasp arms and the selection of clinical fixed-movable prosthetic materials. Clinicians should consider the design of attachments and selection of appropriate manufacturing materials carefully to avoid negative impacts on patients' periodontal support tissues.

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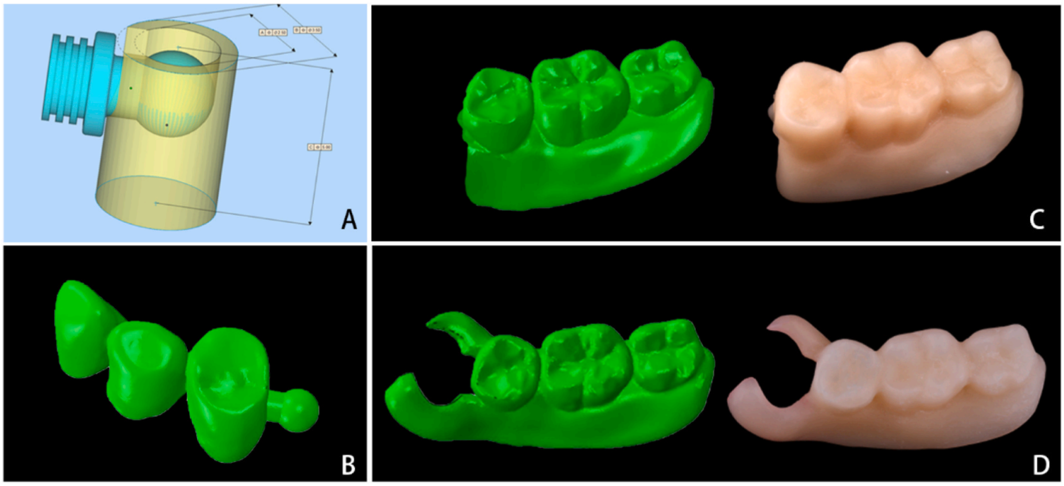

Fig. 1. Integrated prosthesis of crowns and digital Roach attachment. A, Digital design of Roach attachment. B, Integrated prosthesis of Roach attachment positive part. C, Integrated prosthesis of Roach attachment negative part without clasp arms. D, Integrated prosthesis of Roach attachment negative part with clasp arms.

1. Introduction

Fixed-removable prostheses have become a popular treatment option for elderly patients with dentition defects who are not eligible for implantation or reject implant prosthesis [1,2]. The Roach attachment, an extra-coronal elastic attachment, serves to connect fixed and movable parts. The positive structure of the Roach attachment assumes a 3/4 sphere form, while the negative structure takes a 3/4 hollow cylinder configuration. Upon merging these two structures, the negative component effectively interrupts stress and safeguards abutments via its vertical, buccal, and lingual micro mobility [3,4]. Studies have shown that using two to three abutments in fixed-removable prostheses has a better effect on dispersing stress concentration [4,5].

However, the conventional production method of fixed-removable prostheses connected by attachment is complex and expensive, requiring high processing accuracy and special equipment such as grinding instruments and welding machines [6]. Certain metal attachments require special metal adhesives or welding to be fixed to the scaffold of the removable partial denture, while other parts need to be fixed to the metal crown of abutment teeth through physical retention and other methods [7]. With the widespread clinical application of all-ceramic crowns, welding Roach attachment to porcelain-fused-to-metal crowns is no longer feasible, necessitating further investigation into alternative methods of establishing a connection between the attachment and prosthesis. A recent study conducted by researchers investigated the effects of lever arm, tooth preparation, and attachment fixation on stress distribution at the interface between teeth and zirconia attachments. The positively charged components of the zirconia Roach were glued onto the crown, while the negatively charged components were connected to the movable denture. Finite element analysis and in vitro studies were used to evaluate the impact of these factors on stress distribution. The findings suggest a potential clinical application of zirconia attachments and provide new ways for the production of attachments [4].

Based on the utilization of digital dental design and industrial modeling software, the integration of crowns and positive Roach attachment structures, as well as removable partial and negative structures can be designed, whereby the bonding or welding interface can be eliminated [8,9]. The digital processing methodology provides enhanced production efficiency, minimized process complexity and reduced production costs. This particular methodology is particularly well-suited for patients with Kennedy class I mandibular edentulous conditions. Nonetheless, research pertaining to such integrated prosthesis designs remains scarce both domestically and internationally. Furthermore, the addition of clasp arms can improve the retention of removable partial dentures [10]. However, no definitive conclusion has been reached regarding whether the force of the abutment teeth is within acceptable ranges with the incorporation of clasp arms, in cases of fixed-removable prostheses with digital Roach attachments used in free end of the dentition defects.

The importance of attachment design and manufacturing material selection cannot be overstated, as the use of attachments with suboptimal design or inappropriate materials can result in reduced retention and negatively impact periodontal support tissues [11,12]. Notably, the addition of clasp arms to movable dentures may enhance retention force, but requires experimental investigation to determine appropriate prosthetic materials and to obtain guidance for clinical design through experimental research. In this study, we aimed to investigate the effect of different designs of movable parts and prosthetic materials on the stress distribution of supporting tissues in mandibular free end dentition defects using three-dimensional finite element analysis of digital Roach attachments. We expect our findings to provide a reference for selecting suitable clinical fixed-movable prosthetic materials.

Table 1
Material parameters for integrated prosthesis with crown and the positive part of Roach attachment.

Materials	Elasticity modulus (GPa)	Poisson's ratio (ν)	Bending strength (MPa) (Mean ± Standard deviation)
Conventional zirconia	210.00	0.30	914.75 ± 68.12
Ultra-translucent zirconia	209.30	0.32	582.00 ± 20
PEEK	3.74	0.30	170.37 ± 19.31
Lithium disilicate	95.00	0.30	376.90 ± 76.2
Nanoceramic resin	12.80	0.30	202.10 ± 17.9
CAD/CAM resin composite (Paradigm MZ100, 3 M ESPE)	16.00	0.30	189.70 ± 28.2

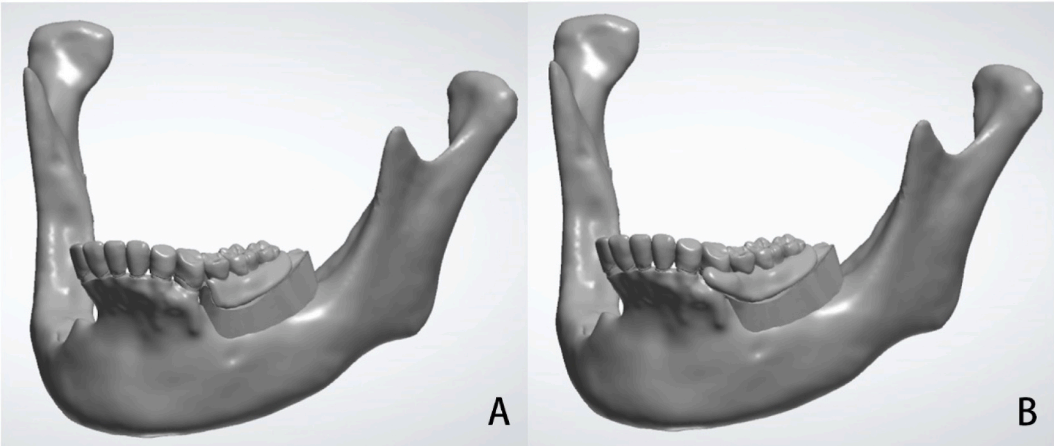

Fig. 2. Digital Roach attachment with optimal design. A, Design 1, excluding the design of clasp arms. B, Design 2, including the design of clasp arms.

2. Materials and methods

The following steps were carried out for modeling and three-dimensional finite element analysis:

2.1. First, a patient with bilateral mandibular second premolar and molar loss, as well as loss of the right canine and first premolar, was identified, and the STL format file was imported into digital dental design software (exocad v2.4, exocad GmbH) to create two integrated fixed-movable joint prostheses with Roach attachments. One design included buccal and lingual clasp arms, while the other did not. The size of the Roach attachment was designed based on the standard size, with a spherical diameter of the positive part set at 2.5 mm (Fig. 1A) [3,4]. The positive part was integrated with the crown, while the negative part was embedded into the removable partial denture to form a buckle structure that was vertically dislocated and in place [4]. Data for both designed prostheses and the mandibular model were exported in STL format. Additionally, we obtained patient consent, and collected DICOM data from CBCT scans.

2.2. CBCT DICOM data of the patient were obtained and imported into Mimics 10.01 software (Materialise GmBH), followed by reconstruction of the jaw shape in 3D and saving in STL format. The file was optimized in Geomagic studio 2013 software (Raindrop GmBH) and exported to Hypermesh 9.0 finite element processor (Altair Engineering GmBH) in STL format for further cleaning. A three-dimensional finite element mesh model of the jaw was generated using four-node tetrahedral elements.

2.3. The root and tooth shapes of the patient were also saved in STL format, refined in 3-matic software (Materialise GmBH), and each tooth containing clear tooth root shapes was saved separately in STL format files, which were then matched with the model scan data. Finally, the crown part of each tooth was replaced with the scanned crown data, and the surface optimization and meshing steps of each tooth are the same as before.

2.4 An offset tool was used in 3-matic to generate a practical model of the periodontal membrane with a thickness of 0.2 mm. the surface optimization and meshing steps are the same as before.

2.5. The integrated prostheses of the dental crown and attachment positive parts, as well as the movable dentures with and without clasp arms, were processed through CAD/CAM cutting methods (Fig. 1B–D). The STL format file of the designed prosthesis was re-imported into Geomagic studio software, and the attachment positive parts were connected to three dental crowns by connecting and segmentation of the dental crowns. The model was re-exported to the Hypermesh 9.0 finite element processor for meshing with four-node tetrahedral elements to generate a three-dimensional finite element mesh model of integrated prosthesis of crowns and digital Roach attachment. The material parameters of the integrated prosthesis of dental crown and attachment positive part were set to conventional zirconia, ultra-translucent, PEEK, Lithium disilicate, Nanoceramic resin, and CAD/CAM resin composite (Paradigm

Table 2
Finite element analysis of related parameters.

	Materials	Elasticity modulus (MPa)	Poisson's ratio (ν)	Size
Root of tooth	Dentin	18,600	0.31	–
Periodontal ligament	–	68.9	0.45	The periodontal space 0.2 mm
Bonding	Panavia F2.0	10,000	0.35	Thickness 1.0 mm
Cortical bone	–	13,700	0.30	–
Mucosa	–	19.6	0.30	Thickness 1.5 mm
RPD	Resin	4500	0.35	–

MZ100, 3 M ESPE). The parameters of the movable parts were set to CAD/CAM cutting resin. Parameter setting was shown in Table 1 [13–15].

2.6. The model data were imported into the finite element analysis software Abaqus/CAE (Abaqus) to carry out finite element analysis to explore the impact of different movable-part designs and the effect of different materials on the stress distribution of the periodontal ligament of the abutment, the mucosa of the edentulous area and the attachment point.

Design 1: fixed-removable prostheses with digital Roach attachment, excluding clasp arm (Fig. 2A).

Design 2: fixed-removable prostheses with digital Roach attachment, including the design of buccal and lingual clasp arms. The design of the clasps follows standard dimensions, with a tip thickness of 1 mm and a shoulder thickness of 2 mm (the buccal clasp arm acts as retentive arm and the undercut is 5 mm, the lingual clasp arm acts as reciprocal arm) [16] (Fig. 2B).

Loading method: A vertical load of 20 N was applied to the second premolar of removable part at the free end, and apply a vertical load of 40 N was applied to the 2 M, summing to 100 N [17,18].

CAD/CAM cutting resin was selected as the material of removable partial denture, and the relevant parameters of finite element analysis of each part are shown in Table 2 [19–22]. The friction coefficient was set to 0.1 for the sliding friction contact between the positive and negative parts of the Roach attachment, and contact surface allowed vertical and buccal-lingual trace movement and small rotation around the horizontal central axis of the sphere [21,22]. The sliding friction contact between the denture base tissue surface and alveolar ridge mucosa was set as a small displacement, with a friction coefficient of 0.1 [19]. Stress distribution for each design with different fixed-component materials was compared.

The present study was approved by the Medical Ethics Committee of West China Hospital, Sichuan University, with the approval number WCHSIRB-D-2021-405.

3. Results

3.1. *A stress analysis was carried out on the periodontal ligament*

The present study focused on the stress analysis of periodontal ligament in relation to the proximal, distal and root apex of the first premolar, canine and lateral incisor.

Our results indicate that regardless of the design method, six groups of models with different prosthetic materials exhibited the maximum stress value of the buccal neck of the lateral incisor periodontal membrane, and the maximum compressive stress value of the distal neck and apical of the first premolar in the PEEK group was the smallest, followed by the Nanoceramic resin group and the CAD/CAM resin composite group. Conversely, the maximum stress values of buccal and distal neck of periodontal ligament in the conventional zirconia group and the ultra-translucent zirconia group were found to be the largest among the six groups under the same design (as illustrated in Fig. 3 and Figs. 1). Furthermore, when the materials of fixed parts were similar, it was found that the maximum stress value of the buccal neck of the periodontal membrane, the maximum compressive stress value of the distal neck of the first premolar and the maximum tensile stress value of the root apex of design 2 were larger than those of the design 1. Specifically, in the PEEK group, the maximum stress value of the buccal neck of the lateral incisors in design 2 was 1.78 MPa, higher than in design 1 (1.77 MPa), the maximum compressive stress of the distal neck of the first premolar was 0.783 MPa, larger than in design 1 (0.774 MPa), and the maximum apical tensile stress was 0.525 MPa, larger than 0.519 MPa in design 1. Moreover, in the conventional zirconia group and the ultra-translucent zirconia group, the maximum stress value of the periodontal membrane in design 2 was 2.64 MPa, which was higher than 2.34 MPa in the same group of design 1, as illustrated in Fig. 3.

In summary, the conventional zirconia group and the ultra-translucent zirconia group exhibited the highest stress values in the periodontal ligament, while the PEEK group had the lowest stress values. Moreover, when the materials of the fixed components were kept consistent, it was observed that design 2 resulted in higher stress values in the periodontal ligament compared to design 1.

3.2. *A stress analysis was conducted on the junction of attachment*

Fig. 4 shows that in design 1, the Von Mises stress levels at the junction of attachment were 113.1 MPa and 110.8 MPa for the conventional zirconia group and the ultra-translucent zirconia group, respectively, both higher than the PEEK group which had a Von Mises stress level of 73.2 MPa. Similarly, in design 2, the Von Mises stress levels of the conventional zirconia group and the ultra-translucent zirconia group were 122.6 MPa and 120.0 MPa correspondingly, both greater than the Von Mises stress level of 73.62 MPa observed in the PEEK group. Our results indicate that under the same design, the Von Mises stress levels of the attachment were

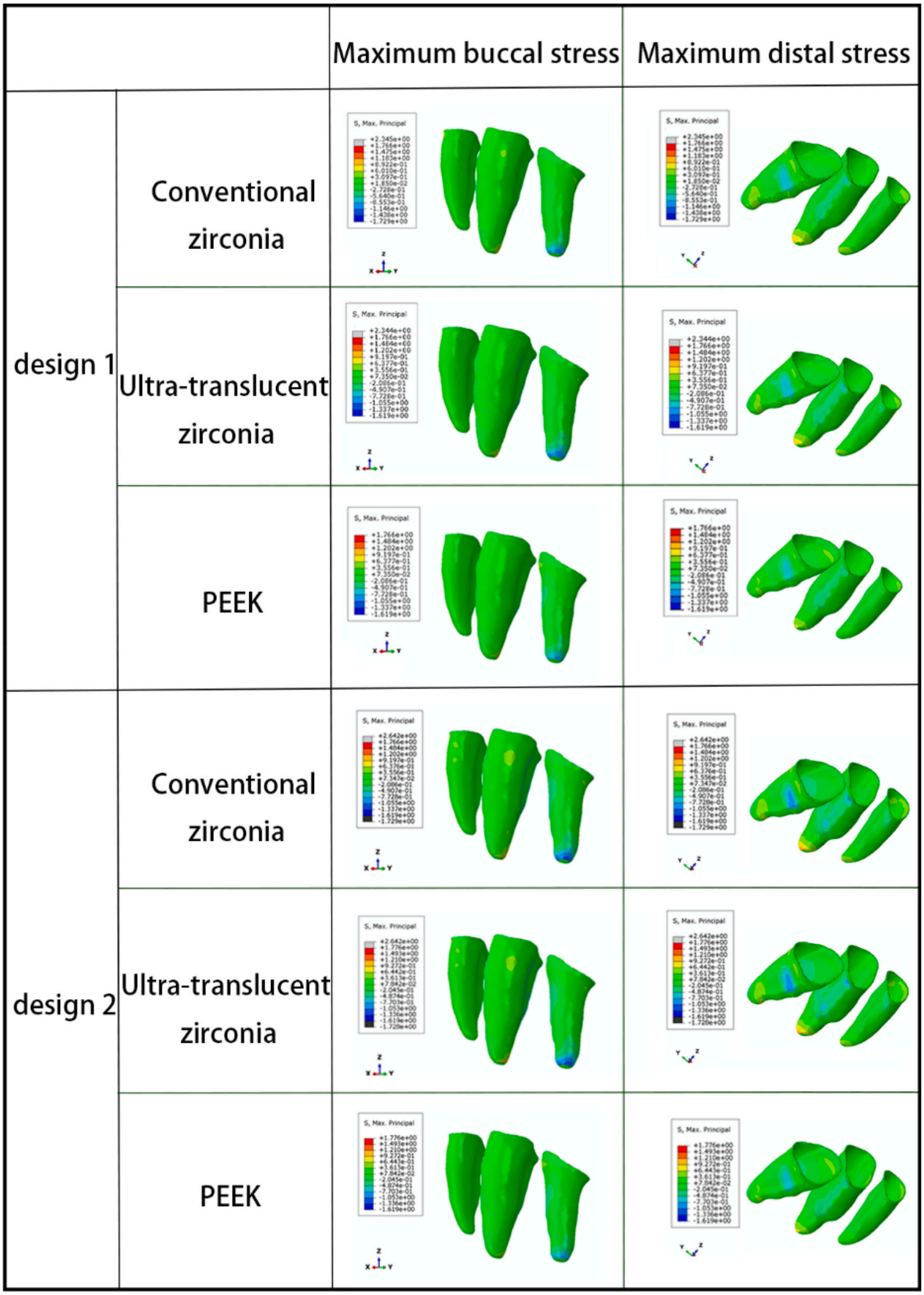

Fig. 3. Distribution of periodontal membrane stress.

higher for groups with higher elastic modulus.

It was found that the Von Mises stress levels of the attachment were positively correlated with the elastic modulus of the material. Additionally, when the materials of the fixed components were consistent, it was observed that design 2 had higher Von Mises stress compared to design 1. Furthermore, it should be noted that at the same characteristic position, the maximum tensile stress values of all

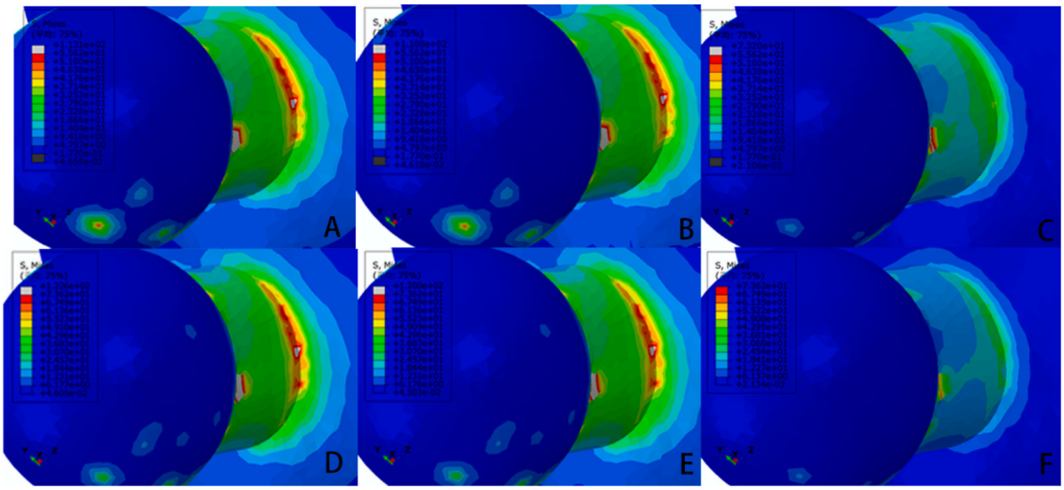

Fig. 4. Von Mises stress distribution of the attachment. A, B, C correspond to the conventional zirconia group, the ultra-translucent zirconia group, and the PEEK group of design 1 respectively. D, E, F correspond to the conventional zirconia group, the ultra-translucent zirconia group, and the PEEK group of design 2 respectively.

groups were found to be lower than the flexural strength of the prosthesis material.

3.3. An analysis of stress and displacement distribution was carried out on the mucosa

Fig. 5 demonstrates that the maximum compressive stress, Von Mises stress and displacement values of the six models in design 1 and design 2 were primarily concentrated in the area where the distal denture contacted the mucosa.

Among the six groups, the maximum compressive stress, Von Mises stress and displacement values of mucosa in the PEEK group were the highest under the same design. In design 1, the maximum compressive stress value was 0.735 MPa for the PEEK group, while the minimum was 0.722 MPa for the conventional zirconia group and the ultra-translucent zirconia group. Similarly, in design 2, the maximum compressive stress value was also 0.735 MPa for the PEEK group, whereas the minimum was 0.695 MPa for the conventional zirconia group and the ultra-translucent zirconia group. For Von Mises stress, the maximum was observed in the PEEK group with a value of 4.190 MPa in design 1, and 4.191 MPa in design 2. The minimum values were found to be 4.132 MPa for the conventional zirconia group and the ultra-translucent zirconia group in design 1, and 4.113 MPa for the same groups in design 2. When it comes to displacement, the PEEK group had the largest displacement value of 0.217 mm in design 1, whereas the conventional zirconia group and the ultra-translucent zirconia group had the smallest displacement value of 0.215 mm. In design 2, the PEEK group had the largest displacement value of 0.217 mm, while the smallest was seen in the conventional zirconia group and the ultra-translucent zirconia group with a value of 0.213 mm.

In the same design, the PEEK group demonstrated the highest values for maximum compressive stress, Von Mises stress, and displacement among the six groups. Additionally, when using the same restorative material, these values consistently exhibited higher magnitudes in design 1 as compared to design 2.

4. Discussion

The present study leveraged advanced digital technology to attain optimized designs of movable parts, whereby clasp arms offered significant benefits in terms of protective effects on mucous membranes. Upon analyzing the mucosal stress, Von Mises stress, maximum stress, and displacement values, it became evident that the clasp arm design elicited relatively lower values across all parameters. Although the clasp arm design led to higher values for maximum stress in the periodontal membrane, the difference in stress between the two designs at corresponding positions did not exceed 0.3 MPa. Notably, the maximum stress values for both designs remained within the threshold of abutment teeth. The enhanced stability and retention force of dentures have been attributed to the clasp arms. In design 2, the buccal arm of the clasp design was designed to enter the buccal undercut of the crown by 0.25 mm, while the lingual arm was placed in confrontation with the buccal arm. By doing so, the clasp arm could more effectively transmit stress to the abutment teeth, while augmenting denture stability and retention and also safeguarding the abutment teeth [6]. Additionally, the Roach attachment's positive and negative structures when combined provide vertical and buccolingual micro mobility to the negative component, which leads to stress interruption and further reinforces the safeguarding effects on the supporting teeth [3]. Thus, the study indicates the feasibility of including clasp arms in clinical designs for patients with compromised mucosa conditions. Further clinical trials are required to verify the effectiveness, durability, and patient satisfaction associated with this design.

With the emergence of CAD/CAM technology and the advent of new materials such as zirconia, PEEK, and CAD/CAM cutting resin, have provided an opportunity to explore alternative approaches to connecting attachments and prosthesis. Due to the various

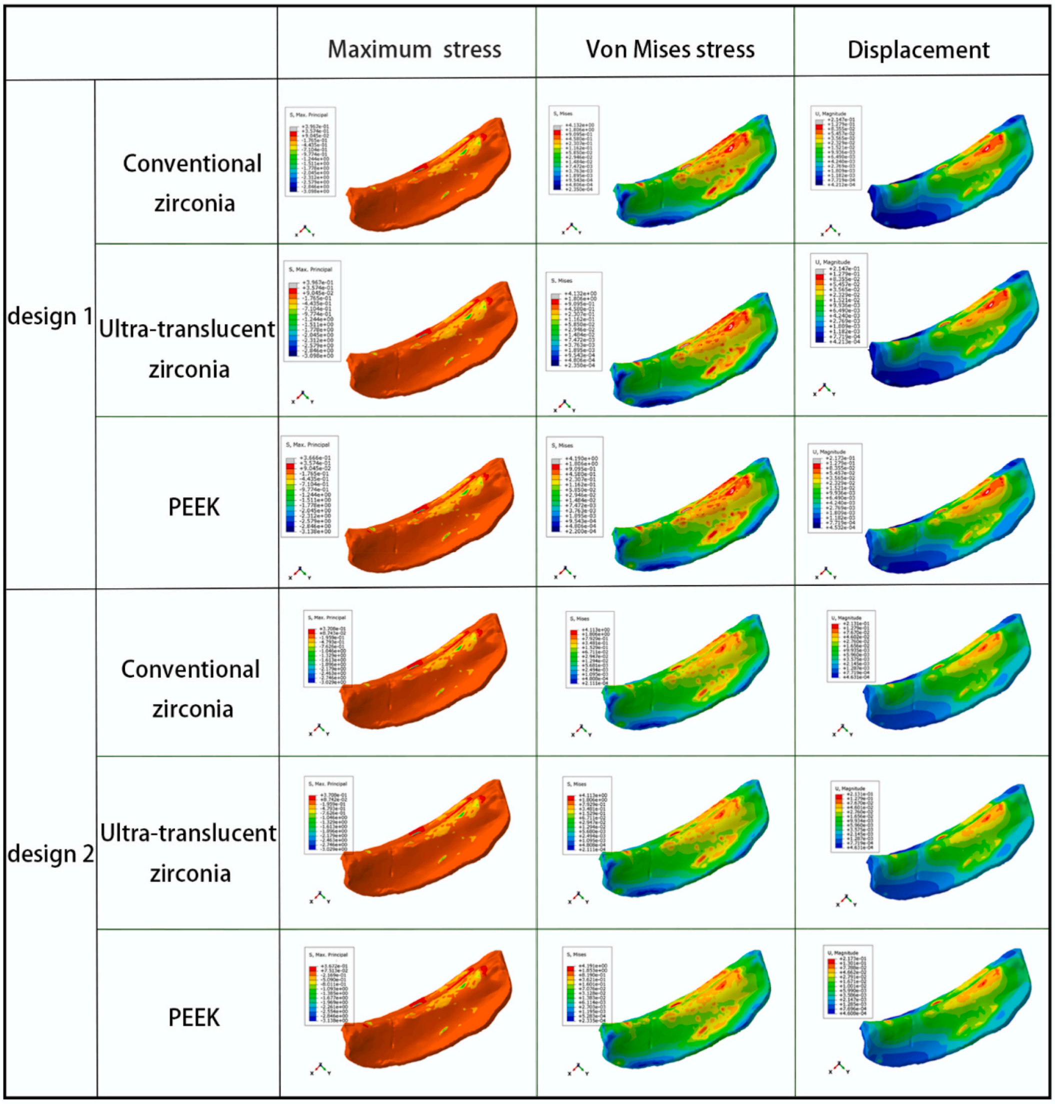

Fig. 5. The stress distribution and displacement distribution of the edentulous mucosa.

properties of restorative materials, it is necessary to consider whether the properties of the materials meet the design requirements in clinical.

The study findings indicate that when low elastic modulus materials, including PEEK, cutting resin, and resin-infiltrated ceramic materials, are utilized as an integrated prosthesis of crowns and Roach attachments, larger stress and displacement on the mucosa are observed. Previous research has determined that the use of PEEK framework can serve as a protective measure for the periodontal membrane, making it a viable option for patients with poor periodontal conditions. However, when subjected to masticatory forces, denture stability is compromised and mucosal stress is heightened, suggesting that PEEK may not be appropriate for certain types of edentulous cases [23], as supported by the results of this study. Moreover, it is imperative to conduct further clinical trials to assess the durability of PEEK prostheses [24]. While resin infiltrated ceramic materials and CAD/CAM cutting resins have been proven to possess adequate wear resistance and are suitable for prosthesis fabrication, their inferior strength necessitates greater material thickness [25], rendering them unsuitable for use in integrated prostheses containing crowns and Roach attachments.

Utilizing materials with high elastic modulus, such as conventional zirconia and ultra-translucent zirconia, in the fabrication of integrated prosthesis containing crowns and Roach attachments can elicit reduced mucosal stress and displacement. While abutment teeth may experience greater force, it remains within their tolerable range, and the attachment interface experiences higher forces yet possesses lower failure rates. In light of these findings, high strength materials like conventional zirconia and ultra-translucent zirconia are recommended for use in the fixed component of Roach attachments. Conventional zirconia and zirconia reinforced glass ceramics, with higher strength and hardness than other materials, can be used for full crown prosthesis and inlay prosthesis of posterior teeth [26]. Ultra-translucent zirconia, a new type of prosthesis material, is helpful to solve the aesthetic problem of conventional zirconia

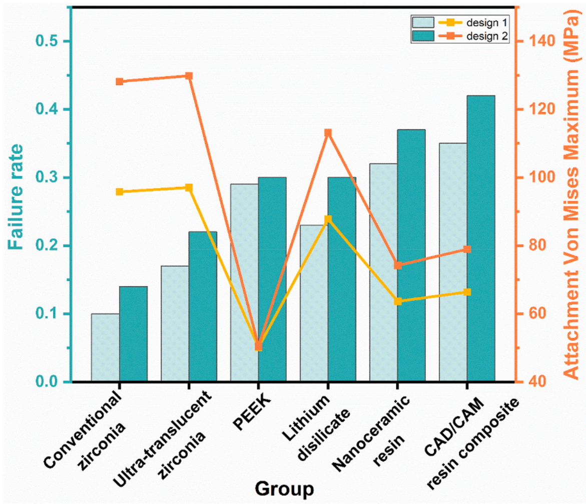

Fig. 6. Comparison of failure rate and maximum stress of the attachment junction.

and can be used as single crowns and fixed bridges of anterior teeth [27–31]. The crystal phase structure of ultra-translucent zirconia is characterized by its stability, resulting in improved mechanical strength and surface performance [29,32,33].

The unique properties of zirconia and ultra-translucent zirconia render them optimal for use in the fixed component of Roach attachments, as their low deformation under stress allows for efficient stress transmission and dispersion to the attachment and abutment teeth, resulting in reduced mucosal stress and displacement. Hence, high elastic modulus materials are recommended for patients with favorable abutment teeth but poor edentulous mucosal conditions. Additionally, materials with high elastic modulus demonstrate greater resistance to fracture, with failure rates calculated by determining the maximum stress-to-bending strength ratio of the material using finite element analysis (as shown in Fig. 6). Although these materials exhibit higher stress at the attachment interface due to greater force transmission and dispersion from the prosthetic device, they still maintain lower failure rates when compared to other materials, with their Von Mises stress remaining below the bending strength of the prosthesis material. Furthermore, digital optimization designs eliminate the need for conventional bonding or welding interfaces, thus reducing the potential damage to the adhesive interface between the attachment and restorative material. These materials also possess robust surface stability and wear resistance, making them better suited for digital Roach attachment optimization design than resin materials. However, this investigation is an in vitro study, necessitating further clinical experimentation to ascertain the effectiveness, durability, and patient satisfaction of the Roach attachment in individuals with different abutment teeth and periodontal conditions.

5. Conclusion

For Roach attachments, it is recommended to use high strength materials such as conventional zirconia and ultra-translucent zirconia in the fixed section, as well as optimized design of the movable parts featuring clasp arms for patients with poor mucosal condition to provide improved protection for mucosal soft tissue. This study establishes a theoretical foundation for the clinical application of prosthetic devices with Roach attachments and provides material selection recommendations. Furthermore, the exploration of the rationality of optimal design in this experiment has yielded practical implications for the field of dental implantology.

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Ethics declarations

This study was reviewed and approved by the Medical Ethics Committee of West China Hospital of Sichuan University, with approval number: WCHSIRB-D-2021-405.

All participants provided informed consent to participate in the study.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Yun Huang: Writing – review & editing, Writing – original draft, Project administration, Investigation, Formal analysis. **Jingrong Wang:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Liqing Zhu:** Investigation, Data curation. **Liren Liu:** Resources, Investigation. **Shanshan Gao:** Visualization, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e23283.

References

[1] T.C. Yang, Y. Maeda, T. Gonda, Clinical performance and satisfaction of removable prostheses with self-adjusting magnetic attachments, J. Prosthet. Dent 111 (2) (2014 Feb) 131–135, https://doi.org/10.1016/j.prosdent.2013.07.001.

[2] A. Mercouriadis-Howald, N. Rollier, S. Tada, G. McKenna, et al., Loss of natural abutment teeth with cast copings retaining overdentures: a systematic review and meta-analysis, J Prosthodont Res 62 (4) (2018 Oct) 407–415, https://doi.org/10.1016/j.jpor.2018.05.002.

[3] D.R. Burns, J.E. Ward, Review of attachments for removable partial denture design: 1. Classification and selection, Int. J. Prosthodont. (IJP) 3 (1990 Jan-Feb) 98–102. PMID: 2196898.

[4] K. Orujov, W. Winter, M. Karl, S. Heckmann, et al., Adhesive removable partial denture attachments made from zirconia ceramic: a finite element analysis and in vitro study, J. Prosthet. Dent 127 (2) (2022 Feb) 302–307, https://doi.org/10.1016/j.prosdent.2020.08.050.

[5] Y.H. Ling, F.Q. Zhang, J.L. Han, Effect of stress distribution of support tissues using attachment prostheses with different number of abutment, Shang Hai Kou Qiang Yi Xue 15 (6) (2006 Dec) 632–636. Chinese. PMID: 17533718.

[6] N.U. Zitzmann, U. Rohner, R. Weiger, G. Krastl, When to choose which retention element to use for removable dental prostheses, Int. J. Prosthodont. (IJP) 22 (2) (2009 Mar-Apr) 161–167. Erratum in: Int J Prosthodont. 2009 May–Jun;22(3):286. PMID: 19418863.

[7] K.C. Oh, B.S. Yun, J.H. Kim, Accuracy of metal 3D printed frameworks for removable partial dentures evaluated by digital superimposition, Dent. Mater. 38 (2) (2022 Feb) 309–317, https://doi.org/10.1016/j.dental.2021.12.012.

[8] Â.R.T.C. Segundo, S. Saraiva, C. de Castro, N. Sesma, et al., CAD-CAM natural restorations-Reproducing nature using a digital workflow, J. Esthetic Restor. Dent. (2023 Feb 23), https://doi.org/10.1111/jerd.13028.

[9] T. Nagayama, J. Wada, C. Watanabe, N. Murakami, et al., Influence of retainer and major connector designs of removable partial dentures on the stabilization of mobile teeth: a preliminary study, Dent. Mater. J. 39 (2020) 89–100, https://doi.org/10.4012/dmj.2018-272.

[10] E. Feinberg, Precision attachment case restoration with implant abutments: a review with case reports, J. Oral Implantol. 37 (2011) 489–498, https://doi.org/10.1563/AAID-JOI-D-10-00009.1.

[11] H.I. Nassar, M.S. Abdelaziz, Retention of bar clip attachment for mandibular implant overdenture, BMC Oral Health 22 (1) (2022 Jun 9) 227, https://doi.org/10.1186/s12903-022-02262-7.

[12] M.R. Campos, J.A. Marcondes Agnelli, A. Cândido Dos Reis, Factors influencing retention and durability of attachments for overdentures - adverse effects of cleansings, pH, and temperature: a systematic review, Heliyon 8 (12) (2022 Dec 17), e12411, https://doi.org/10.1016/j.heliyon.2022.e12411.

[13] G.S. de Andrade, J.P. Tribst, A.O. Dal Piva, M.A. Bottino, et al., A study on stress distribution to cement layer and root dentin for post and cores made of CAD/CAM materials with different elasticity modulus in the absence of ferrule, J Clin Exp Dent 11 (2019) e1–e8, https://doi.org/10.4317/jced.55295.

[14] J.P.M. Tribst, A.M.O. Dal Piva, A.L.S. Borges, R.M. Araújo, 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. 36 (2020) 179–186, https://doi.org/10.1016/j.dental.2019.11.022.

[15] J. Yan, M.R. Kaizer, Y. Zhang, Load-bearing capacity of lithium disilicate and ultra-translucent zirconias, J. Mech. Behav. Biomed. Mater. 88 (2018) 170–175, https://doi.org/10.1016/j.jmbbm.2018.08.023.

[16] Y. Akiyama, M. Kanazawa, M. Iwaki, T. Hada, et al., Fabrication of milled removable partial dentures using a custom plate with prefabricated artificial teeth, J Prosthodont Res (2023 Feb 2), https://doi.org/10.2186/jpr.JPR_D_22_00100.

[17] J.Q. Wang, Y. Zhang, M. Pang, Y.Q. Wang, et al., Biomechanical comparison of six different root-analog implants and the conventional morse taper implant by finite element analysis, Front. Genet. 13 (2022 Jun 13), 915679, https://doi.org/10.3389/fgene.2022.915679.

[18] M.M. Amer, H.A. Rashad, S. Abdallah, Stress distribution of implant retained obturators using different types of attachments: a three dimensional finite element analysis, Tanta Dental Journal 12 (2015) 30–40, https://doi.org/10.1016/j.tdj.2015.09.001.

[19] H.Y. Wang, Y.M. Zhang, D. Yao, J.H. Chen, Effects of rigid and nonrigid extracoronal attachments on supporting tissues in extension base partial removable dental prostheses: a nonlinear finite element study, J. Prosthet. Dent 105 (2011) 338–346, https://doi.org/10.1016/S0022-3913(11)60066-8.

[20] S.C. Dogru, E. Cansiz, Y.Z. Arslan, A review of finite element applications in oral and maxillofacial biomechanics, J. Mech. Med. Biol. 18 (2018), https://doi.org/10.1142/S0219519418300028.

[21] E.P. Pellizzer, F.R. Verri, R.M. Falcón-Antenucci, M.C. Goiato, et al., Evaluation of different retention systems on a distal extension removable partial denture associated with an osseointegrated implant, J. Craniofac. Surg. 21 (2010) 727–734, https://doi.org/10.1097/SCS.0b013e3181d8098a.

[22] M.I. El-Anwar, S.A. Yousief, T.A. Soliman, M.M. Saleh, et al., A finite element study on stress distribution of two different attachment designs under implant supported overdenture, Saudi Dent J 27 (2015) 201–207, https://doi.org/10.1016/j.sdentj.2015.03.001.

[23] X. Chen, B. Mao, Z. Zhu, J. Yu, 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. 9 (2019), 13975, https://doi.org/10.1038/s41598-019-50363-1.

[24] I. Papathanasiou, P. Kamposiora, G. Papavasiliou, M. Ferrari, The use of PEEK in digital prosthodontics: a narrative review, BMC Oral Health 20 (2020) 217, https://doi.org/10.1186/s12903-020-01202-7.

[25] N.C. Lawson, R. Bansal, J.O. Burgess, Wear, strength, modulus and hardness of CAD/CAM restorative materials, Dent. Mater. 32 (2016) e275, https://doi.org/10.1016/j.dental.2016.08.222. –e83.

[26] S. Jagodin, M. Sasse, S. Freitag-Wolf, M. Kern, Influence of attachment design and material on the retention of resin-bonded attachments, Clin. Oral Invest. 23 (2019) 1217–1223, https://doi.org/10.1007/s00784-018-2544-5.

[27] S.E. Elsaka, Optical and mechanical properties of newly developed monolithic multilayer zirconia, J. Prosthodont. 28 (2019) e279–e284, https://doi.org/10.1111/jopr.12730.

[28] P. Baldissara, V.F. Wandscher, A.M.E. Marchionatti, C. Parisi, et al., Translucency of IPS e.max and cubic zirconia monolithic crowns, J. Prosthet. Dent 120 (2018) 269–275, https://doi.org/10.1016/j.prosdent.2017.09.007.

[29] E.M. Muñoz, D. Longhini, S.G. Antonio, G.L. Adabo, The effects of mechanical and hydrothermal aging on microstructure and biaxial flexural strength of an anterior and a posterior monolithic zirconia, J. Dent. 63 (2017) 94–102, https://doi.org/10.1016/j.jdent.2017.05.021.

[30] M. Carrabba, A.J. Keeling, A. Aziz, A. Vichi, et al., Translucent zirconia in the ceramic scenario for monolithic restorations: a flexural strength and translucency comparison test, J. Dent. 60 (2017) 70–76, https://doi.org/10.1016/j.jdent.2017.03.002.

[31] L. Mao, M.R. Kaizer, M. Zhao, B. Guo, et al., Graded ultra-translucent zirconia (5Y-psz) for strength and functionalities, J. Dent. Res. 97 (2018) 1222–1228, https://doi.org/10.1177/0022034518771287.

[32] F. Zhang, M. Inokoshi, M. Batuk, J. Hadermann, et al., Strength, toughness and aging stability of highly-translucent Y-TZP ceramics for dental restorations, Dent. Mater. 32 (2016) e327–e337, https://doi.org/10.1016/j.dental.2016.09.025.

[33] B.D. Flinn, A.J. Raigrodski, L.A. Mancl, R. Toivola, et al., Influence of aging on flexural strength of translucent zirconia for monolithic restorations, J. Prosthet. Dent 117 (2017) 303–309, https://doi.org/10.1016/j.prosdent.2016.06.010.