

FINITE ELEMENT ANALYSIS AS A TOOL FOR DIGITAL OPTIMIZATION OF REMOVABLE PARTIAL DENTURE CLASPS: CURRENT EVIDENCE AND FUTURE PERSPECTIVES

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ABSTRACT

The digital transformation of removable partial denture (RPD) fabrication has expanded the possibilities for optimizing clasp design through computer-aided technologies and biomechanical simulation. This narrative review explores the role of finite element analysis (FEA) as a tool for guiding digital clasp design, focusing on its applications in biomechanical assessment, material selection, and prosthetic optimization. Current evidence demonstrates that FEA can effectively evaluate stress distribution, deformation, retention, and fatigue behavior, providing valuable insights into the biomechanical performance of clasp-retained prostheses before clinical implementation. The review highlights the influence of clasp geometry and material properties on biomechanical behavior and discusses the performance of conventional cobalt-chromium alloys, titanium, and high-performance polymers such as PEEK and PEKK. By enabling virtual testing under standardized conditions, FEA supports evidence-based design decisions and facilitates the development of more predictable and individualized prosthetic solutions. Nevertheless, the accuracy of finite element simulations remains dependent on model assumptions and simplifications, emphasizing the need for continued experimental and clinical validation. Future integration of artificial intelligence, patient-specific modeling, and digital twin technologies may further enhance the precision and clinical relevance of digital prosthodontic workflows. Overall, finite element analysis represents a valuable decision-support tool capable of guiding digital clasp design and optimization within contemporary removable prosthodontics.

Key words: *removable partial denture, clasp design, finite element analysis, digital dentistry, biomechanics, CAD/CAM*

INTRODUCTION

Removable partial dentures (RPDs) continue to play an important role in the rehabilitation of partially edentulous patients. Despite the increasing use of implant-supported restorations, conventional RPDs remain a widely accepted treatment option due to their affordability, clinical versatility, and applicability in a broad range of clinical situations. Recent evidence has shown that both conventional and implant-assisted removable partial dentures can significantly improve oral function, patient satisfaction, and quality of life when appropriately designed and maintained [1,2].

The success of an RPD depends on the harmonious interaction between the prosthesis, abutment teeth, and supporting tissues. Among its components, direct retainers (clasps) are essential for providing retention and stability while ensuring an adequate distribution of functional loads [3]. The biomechanical behavior of a clasp is influenced by several factors, including its geometry, material properties, manufacturing method, and the depth of the selected undercut. Inadequate clasp design may compromise retention, increase stress concentration, and negatively affect both the prosthesis and the supporting structures

[3,4].

In recent years, digital technologies have profoundly transformed prosthodontic workflows [5]. The integration of computer-aided design and computer-aided manufacturing (CAD/CAM) systems has enabled more efficient and reproducible approaches to prosthesis fabrication [6,7]. These technologies have also expanded into removable prosthodontics, allowing the digital design and fabrication of removable partial denture frameworks and retentive components [8]. Furthermore, advanced manufacturing techniques, including selective laser melting and additive manufacturing, have created new possibilities for the production of highly accurate clasp assemblies and framework structures [9].

Although digital workflows facilitate the design and fabrication of removable partial dentures, predicting the biomechanical behavior of clasp assemblies remains a challenge. Variables such as clasp dimensions, material characteristics, and retentive undercuts interact in a complex manner and may significantly influence retention, deformation, fatigue resistance, and stress distribution. Consequently, objective methods capable of evaluating these parameters before fabrication have become increasingly important in digital prosthodontics [3,4].

Finite element analysis (FEA) has emerged as one of the most widely used computational tools for studying biomechanical behavior in dentistry [10]. By simulating functional loading conditions, FEA allows the evaluation of stress distribution, deformation patterns, and structural performance of dental restorations and prosthetic components. Recent studies have demonstrated its applicability in removable prosthodontics, particularly in the assessment of clasp retention, fatigue behavior, material performance, and stress transmission to supporting structures [11-13].

Therefore, the aim of this narrative review is to evaluate the current evidence regarding the use of finite element analysis

as a tool for the digital optimization of removable partial denture clasp design, with particular emphasis on retention prediction, stress distribution, and the biomechanical influence of design- and material-related factors.

LITERATURE REVIEW

✓ *The evolution of clasp design: from empirical principles to digital workflows*

For decades, the design and fabrication of removable partial dentures have been based on conventional clinical and laboratory procedures. Framework design traditionally relied on diagnostic casts, manual surveying, and the experience of clinicians and dental technicians to determine the optimal path of insertion, clasp configuration, and retentive areas [14]. Although these approaches have proven clinically successful, they are highly dependent on operator skills and may be associated with inaccuracies accumulated throughout the fabrication process [15].

The introduction of digital technologies has significantly changed the workflow of removable prosthodontics. Advances in digital impression systems, virtual surveying, and computer-aided design have enabled the acquisition and processing of clinical data in a more efficient and reproducible manner. According to recent systematic reviews, digital workflows for removable partial dentures have shown promising results regarding data acquisition, maxillomandibular relationship records, and framework design, supporting their increasing integration into daily clinical practice [14,15].

Digitalization has also transformed the fabrication of removable partial denture frameworks. Computer-aided design and computer-aided manufacturing (CAD/CAM) technologies, together with rapid prototyping and additive manufacturing techniques, have provided new possibilities for producing metal frameworks with improved consistency and reduced laboratory variability. Systematic reviews have demonstrated that CAD/CAM-fabricated frameworks can achieve clinically

acceptable levels of fit accuracy comparable to, and in some situations superior to, those obtained through conventional casting procedures [14,16].

These developments have expanded beyond framework fabrication and increasingly involve the production and integration of individual prosthetic components. Recent reports have described the successful incorporation of CAD/CAM denture teeth into cast-metal removable partial denture frameworks, as well as the fabrication of restorations specifically adapted to existing clasp-retained prostheses. Such approaches illustrate the growing flexibility of digital technologies and their potential to support individualized prosthetic rehabilitation [17,18].

More recently, fully digital workflows have been proposed for the duplication and fabrication of clasp-retained removable partial dentures. Three-dimensional scanning, virtual design, and additive manufacturing techniques allow the digital reproduction of existing prostheses while preserving their functional characteristics [19]. These workflows represent an important step toward fully digital removable prosthodontics and demonstrate the ongoing transition from conventional craftsmanship to data-driven design and manufacturing processes.

The continuous evolution of digital technologies, including advances in imaging systems, data acquisition, and manufacturing techniques, is expected to further expand the possibilities of removable prosthodontics. While digital workflows offer improved efficiency, reproducibility, and customization, they also highlight the need for objective methods capable of evaluating the biomechanical performance of prosthetic components before fabrication [15,20]. In this context, the increasing adoption of computational tools has created new opportunities for optimizing removable partial denture design and improving clinical predictability.

The increasing complexity of removable partial denture design has stimulated the adoption of computational

methods capable of evaluating biomechanical performance before clinical application. Among these methods, finite element analysis (FEA) has become one of the most widely used numerical tools in dental research. By transforming complex anatomical structures into mathematical models, FEA enables the simulation of functional loading conditions and provides detailed information regarding stress distribution, deformation patterns, strain concentration, and structural behavior. Consequently, FEA has become an important instrument for investigating the biomechanical performance of removable prostheses and their supporting structures [20,21].

One of the major advantages of finite element analysis is its ability to investigate biomechanical phenomena that are difficult to assess experimentally. Unlike conventional laboratory testing, which often evaluates only a limited number of variables, FEA enables the simultaneous analysis of multiple parameters, including stress concentration, strain distribution, displacement, and deformation under controlled loading conditions. Furthermore, virtual models can be repeatedly modified without the costs and limitations associated with physical prototype fabrication, making FEA particularly attractive for the evaluation of removable partial denture components and the optimization of prosthetic designs [21,22].

In removable prosthodontics, finite element analysis has been extensively applied to evaluate the mechanical behavior of distal extension removable partial dentures, implant-assisted removable partial dentures, and different attachment systems [23]. These studies have demonstrated that prosthesis design, implant position, attachment type, and support distribution significantly influence stress transmission to abutment teeth, residual ridges, and implant components [23,24]. The ability of FEA to visualize stress concentration areas has improved the understanding of load transfer mechanisms and contributed to the optimization of prosthetic designs aimed at

minimizing biomechanical complications [25].

More recently, finite element analysis has been increasingly employed to investigate the biomechanical behavior of clasp assemblies. Since retention and stability depend directly on clasp deformation during insertion and removal, numerical simulations have provided valuable insights into the influence of geometric parameters on retentive performance. Chen et al. demonstrated that variations in clasp geometry significantly affect retention force and stress distribution, highlighting the importance of design optimization in achieving predictable biomechanical behavior. Such findings support the concept that clasp performance can be evaluated and refined digitally before fabrication, reducing reliance on empirical decision-making [26].

Finite element studies have also contributed to a better understanding of the relationship between retentive force and biomechanical safety. While increased retention is generally desirable, excessive rigidity may result in elevated stress concentrations within the clasp structure or on the abutment tooth. Consequently, FEA has been increasingly used to identify designs capable of achieving adequate retention while minimizing potentially harmful stress levels. This approach allows researchers to evaluate alternative geometries and optimize clasp performance before fabrication and clinical application [26,27].

Another important application of FEA involves the assessment of fatigue behavior and long-term mechanical durability. During clinical service, clasps are repeatedly subjected to insertion and removal cycles that may eventually lead to deformation or fracture. Probabilistic finite element models have been used to estimate fatigue life and identify critical stress regions within additively manufactured clasp designs. These analyses provide information that is difficult to obtain through conventional laboratory testing alone and may contribute to the development of more durable retentive

components [28].

The integration of finite element analysis with digital design workflows has further expanded the possibilities for prosthetic optimization. Numerical simulations can now be incorporated into the design process to evaluate alternative geometries, attachment configurations, and retentive systems before manufacturing. Huang et al. demonstrated the potential of combining CAD/CAM technologies with three-dimensional finite element modeling to optimize attachment design and improve biomechanical performance. Such approaches illustrate the transition from experience-based design toward evidence-based digital optimization, where virtual testing may support clinical decision-making and improve prosthetic predictability [23,28].

Collectively, the available evidence suggests that finite element analysis has evolved from a research methodology into a valuable design-support tool in removable prosthodontics. By allowing the prediction of stress distribution, deformation patterns, fatigue behavior, retentive performance, and material-specific biomechanical responses, FEA provides a scientific basis for the optimization of clasp geometry and other prosthetic components. These capabilities have become particularly relevant in the era of digital dentistry, where increasingly sophisticated design and manufacturing technologies require equally advanced methods of biomechanical evaluation [21,28].

✓ *Material selection and biomechanical performance*

Material selection is a critical determinant of the biomechanical behavior of removable partial denture clasps. In addition to clasp geometry and undercut depth, the mechanical properties of the selected material directly influence retention, flexibility, deformation, fatigue resistance, and stress transmission to the supporting structures. As digital design workflows continue to evolve, understanding the interaction between

material characteristics and clasp performance has become increasingly important. Finite element analysis has emerged as a valuable tool for investigating these interactions, allowing researchers to predict how different materials respond under simulated clinical conditions [29,30].

For many decades, cobalt-chromium alloys have been regarded as the gold standard for removable partial denture frameworks and clasps. Their high elastic modulus and rigidity allow the fabrication of retentive components capable of maintaining dimensional stability while providing predictable retention. Consequently, cobalt-chromium clasps have frequently served as reference models in both experimental and finite element studies investigating the biomechanical performance of alternative materials. However, the growing demand for metal-free prostheses, improved esthetics, and enhanced patient comfort has stimulated the development of new material options for removable prosthodontics [30,31].

Among these alternatives, polyaryletherketone (PAEK) materials, particularly polyetheretherketone (PEEK) and polyetherketoneketone (PEKK), have attracted considerable interest. These high-performance polymers exhibit favorable biocompatibility, low weight, chemical stability, and elastic properties that differ substantially from those of metallic alloys. Their lower elastic modulus results in greater flexibility during insertion and removal, which may reduce stress concentration on abutment teeth and supporting tissues. At the same time, this increased flexibility may affect retentive performance and require modifications in clasp geometry to achieve clinically acceptable retention [30,32].

Finite element studies have demonstrated that the biomechanical response of a clasp cannot be explained solely by its material properties or geometry, but rather by the interaction between both variables. Materials with lower stiffness tend to exhibit greater deformation under functional loading, whereas more rigid materials may generate higher stress

concentrations within the clasp structure or on the abutment tooth. Consequently, identical clasp designs may behave differently when fabricated from different materials, highlighting the importance of material-specific design strategies [33,34].

Several recent investigations have evaluated the influence of material selection on clasp retention and deformation. Studies involving PEEK and other high-performance polymers have generally reported lower retentive forces compared with conventional cobalt-chromium clasps, although more favorable stress distribution patterns have often been observed [35]. These findings suggest that optimization of clasp dimensions and geometry may compensate for differences in elastic behavior and improve the clinical performance of polymer-based retentive systems [36].

Advances in material engineering have further expanded the range of available options. Modified PEEK materials, fiber-reinforced polymers, and other members of the PAEK family have been developed to enhance mechanical properties while maintaining the biological and esthetic advantages associated with metal-free prostheses. Finite element analyses indicate that reinforcement strategies may improve structural stability and reduce excessive deformation, potentially narrowing the biomechanical differences between polymer-based materials and conventional metallic alloys [32,34].

Titanium has also been investigated as an alternative framework material because of its excellent biocompatibility, corrosion resistance, and favorable strength-to-weight ratio. Systematic reviews comparing titanium, PEEK, and cobalt-chromium frameworks suggest that each material presents distinct biomechanical advantages and limitations. Rather than identifying a universal substitute for cobalt-chromium, current evidence supports a more individualized approach in which material selection is guided by specific clinical requirements and desired biomechanical outcomes [34].

Overall, the available evidence indicates

that material selection plays a decisive role in clasp biomechanics and cannot be considered independently of design parameters. Finite element analysis has significantly improved the understanding of material-dependent behavior by allowing the evaluation of retention, deformation, stress distribution, and fatigue performance before fabrication. These capabilities support the development of material-specific digital design strategies and reinforce the role of FEA as a key tool for the biomechanical optimization of removable partial denture clasps [33-36].

✓ *Advantages and limitations of finite element analysis in clasp design*

The increasing adoption of digital workflows in removable prosthodontics has created a growing need for objective tools capable of predicting the biomechanical behavior of prosthetic components before fabrication. In this context, finite element analysis (FEA) has emerged as one of the most valuable computational methods for evaluating removable partial denture clasp performance under simulated clinical conditions. By enabling the assessment of stress distribution, deformation patterns, retentive behavior, and fatigue resistance, FEA provides information that would be difficult to obtain using conventional experimental approaches alone [37,38].

One of the main advantages of FEA is its ability to support design optimization before manufacturing. Digital models can be modified repeatedly, allowing researchers and clinicians to compare alternative clasp geometries, retentive undercuts, and framework configurations without the need for multiple physical prototypes. This capability is particularly relevant in the context of digital prosthodontics, where virtual design and manufacturing technologies increasingly rely on predictive methods to improve efficiency and clinical predictability [39,40].

Finite element analysis also represents a powerful tool for evaluating the biomechanical implications of material selection. As demonstrated in recent studies,

materials with different elastic properties may exhibit substantially different patterns of deformation, stress concentration, and load transfer despite sharing similar geometric configurations. Through virtual simulations, FEA allows the comparison of material-dependent biomechanical responses and facilitates the development of material-specific design strategies. Such applications have become particularly important with the introduction of high-performance polymers and other alternative materials in removable prosthodontics [38,40].

Another important advantage is the ability of FEA to evaluate the balance between retention and biomechanical safety. While adequate retentive force is essential for prosthesis stability, excessive rigidity may increase stress concentrations within the clasp structure or on the abutment tooth. Finite element models enable the identification of designs capable of achieving satisfactory retention while minimizing potentially harmful stresses, thereby supporting evidence-based optimization of clasp assemblies before clinical application [40].

Despite these advantages, finite element analysis presents several limitations that must be acknowledged. Numerical models inevitably require simplifications regarding geometry, material properties, boundary conditions, and loading scenarios. Biological tissues are often represented as homogeneous and isotropic structures, while prosthetic materials are commonly assumed to behave in a linearly elastic manner. Such assumptions facilitate model construction but may not fully reproduce the complexity of the oral environment and its dynamic functional conditions [40,41].

Another important limitation concerns the lack of methodological standardization among studies. Differences in model construction, mesh density, loading protocols, and material parameters may lead to substantial variability in reported results, making direct comparison between investigations difficult. Furthermore, many finite element studies evaluate isolated mechanical variables and do not account for

biological adaptation, patient-specific functional habits, or long-term clinical changes. Consequently, numerical simulations should not be interpreted as direct predictors of clinical outcomes [42,43].

Nevertheless, the value of finite element analysis lies not in its ability to perfectly replicate clinical reality, but in its capacity to compare alternative designs under controlled and reproducible conditions. By providing a consistent framework for evaluating geometry, materials, and retentive configurations, FEA enables informed decision-making during the design process and reduces reliance on empirical trial-and-error approaches. Therefore, finite element analysis should be considered a complementary decision-support tool that works alongside experimental evidence and clinical experience rather than replacing them [37,42].

Looking forward, the integration of artificial intelligence, advanced imaging systems, and patient-specific digital workflows may further enhance the clinical relevance of finite element models. Artificial intelligence-assisted design platforms have the potential to automate optimization processes, while increasingly sophisticated digital workflows may enable the creation of individualized biomechanical simulations based on patient-specific anatomical and functional data. These developments could significantly improve the predictive value of virtual testing and strengthen the role of FEA within future digital removable prosthodontic workflows [41].

FUTURE PERSPECTIVES

The future of removable partial denture clasp design is expected to move beyond conventional digital workflows toward increasingly predictive and individualized approaches. While current finite element analysis (FEA) applications primarily serve as research and design-support tools, ongoing advances in computational technologies may enable their integration into routine clinical and laboratory workflows. As digital dentistry continues to

evolve, the combination of virtual design environments and biomechanical simulation has the potential to improve treatment planning, optimize prosthetic components, and enhance clinical predictability [44,45].

One of the most promising developments is the integration of artificial intelligence (AI) into digital prosthodontic workflows. AI-based systems have already demonstrated the ability to assist with diagnostic procedures, treatment planning, and prosthetic design. In the context of removable prosthodontics, future applications may include automated clasp design, prediction of retentive performance, and identification of biomechanically favorable configurations based on large clinical and computational datasets. Such systems could reduce operator-dependent variability and facilitate evidence-based decision-making during the design process [45].

Another important direction involves the development of patient-specific finite element models. Most current simulations are based on simplified or idealized geometries that cannot fully represent individual anatomical and functional variations. Advances in digital imaging, data acquisition, and computational processing increasingly allow the creation of personalized biomechanical models capable of incorporating patient-specific anatomical features, periodontal support conditions, and loading scenarios. Such approaches may improve the accuracy and clinical relevance of biomechanical predictions and support more individualized prosthetic designs [46,47].

The concept of digital twins may further expand the role of biomechanical simulation in prosthodontics. By creating dynamic virtual replicas of biological and prosthetic systems, digital twin technology could enable continuous monitoring, simulation, and optimization throughout the lifespan of a prosthetic restoration. Although still in its early stages within dentistry, this technology has the potential to transform finite element analysis from a static evaluation method into a continuously adaptive clinical decision-

support system [48].

Rather than replacing clinical expertise, future digital systems are likely to combine artificial intelligence, patient-specific modeling, and finite element analysis to support evidence-based prosthetic design. The integration of these technologies may transform clasp design from a largely experience-driven process into a predictive, data-driven, and individualized workflow. Within this evolving digital ecosystem, finite element analysis is expected to remain a central tool for optimizing clasp geometry, material selection, and biomechanical performance before clinical application [44,48].

CONCLUSIONS

1. The transition from conventional design principles to digital workflows has transformed removable partial denture fabrication, enabling more precise, reproducible, and customizable clasp designs.
2. Finite element analysis has emerged as a valuable tool for investigating clasp biomechanics by providing detailed information regarding stress distribution, deformation, retention, and fatigue

behavior under simulated clinical conditions.

3. Current evidence indicates that clasp performance depends on the interaction between geometry and material properties. Consequently, digital optimization should be based on material-specific design strategies rather than the direct transfer of conventional clasp configurations between different materials.
4. The principal value of finite element analysis lies in its ability to compare alternative designs under standardized conditions and support evidence-based optimization before fabrication. However, the predictive capacity of FEA remains influenced by model assumptions and methodological limitations, making clinical validation essential.
5. Based on the available evidence, finite element analysis can effectively guide digital clasp design and optimization. Future integration with artificial intelligence, patient-specific modeling, and digital twin technologies may further enhance its role in the development of personalized and predictive removable prosthodontic workflows.

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REFERENCES

1. Bandiaky, O.N.; Lokossou, D.L.; Soueidan, A.; Le Bars, P.; Gueye, M.; Mbodj, E.B.; Le Guéhenne, L. Implant-Supported Removable Partial Dentures Compared to Conventional Dentures: A Systematic Review and Meta-Analysis of Quality of Life, Patient Satisfaction, and Biomechanical Complications. *Clin. Exp. Dent. Res.* **2022**, *8*, 294–312.
2. Drummond, L.B.; Bezerra, A.P.; Feldmann, A.; Gonçalves, T.M.S.V. Long-Term Assessment of the Periodontal Health of Removable Partial Denture Wearers: A Systematic Review and Meta-Analysis. *J. Prosthet. Dent.* **2025**, *134*, 1664–1685.
3. Zheng, J.; Aarts, J.M.; Ma, S.; Waddell, J.N.; Choi, J.J.E. Different Undercut Depths Influence on Fatigue Behavior and Retentive Force of Removable Partial Denture Clasp Materials: A Systematic Review. *J. Prosthodont.* **2023**, *32*, 108–115.

4. Mousa, M.A.; Abdullah, J.Y.; Jamayet, N.B.; El-Anwar, M.I.; Ganji, K.K.; Alam, M.K.; Husein, A. Biomechanics in Removable Partial Dentures: A Literature Review of FEA-Based Studies. *Biomed. Res. Int.* **2021**, *2021*, 5699962.
5. Takaichi, A.; Fueki, K.; Murakami, N.; Ueno, T.; Inamochi, Y.; Wada, J.; Arai, Y.; Wakabayashi, N. A Systematic Review of Digital Removable Partial Dentures. Part II: CAD/CAM Framework, Artificial Teeth, and Denture Base. *J. Prosthodont. Res.* **2022**, *66*, 53–67.
6. Watanabe, H.; Fellows, C.; An, H. Digital Technologies for Restorative Dentistry. *Dent. Clin. North Am.* **2022**, *66*, 567–590.
7. Abduo, J.; Rasaie, V. Digital Workflows in Prosthodontics. *Aust. Dent. J.* **2025**, *70*, S146–S158.
8. Rues, S.; Tasaka, A.; Fleckenstein, I.; Yamashita, S.; Rammelsberg, P.; Boehm, S.; Schwindling, F.S. Fit and Retention of Cobalt-Chromium Removable Partial Denture Frameworks Fabricated with Selective Laser Melting. *J. Funct. Biomater.* **2023**, *14*, 416.
9. Ma, K.; Chen, H.; Shen, Y.; Guo, Y.; Li, W.; Wang, Y.; Zhang, Y.; Sun, Y. Feasibility Study and Material Selection for Powder-Bed Fusion Process in Printing of Denture Clasps. *Comput. Biol. Med.* **2023**, *157*, 106772.
10. Falcinelli, C.; Valente, F.; Vasta, M.; Traini, T. Finite Element Analysis in Implant Dentistry: State of the Art and Future Directions. *Dent. Mater.* **2023**, *39*, 539–556.
11. Odaka, K.; Sugano, M.; Kawamoto, T.; Takano, N.; Matsunaga, S. Finite Element Analysis of Fatigue Life of Commercially Pure Titanium Clasps Additively Manufactured with Different Building Orientations. *Dent. Mater. J.* **2024**, *43*, 656–666.
12. Kamal, M.N.M.; Mohammed, H.A.; Shokry, A. Finite Element Analysis of Stress Distribution in Unilateral Distal Extension Partial Dentures: A Comparison of Four Attachment Designs. *BMC Oral Health* **2025**, *25*, 810.
13. Mousa, M.A.; Husein, A.; El-Anwar, M.I.; Yusoff, N.; Abdullah, J.Y. Evaluation of the Biomechanics of Aramany Class I Obturators of Different Designs Using Numerical and Experimental Methods. Part I: Retention and Associated Stress. *J. Prosthet. Dent.* **2024**, *132*, 1088.e1–1088.e8.
14. Ahmed, N.; Abbasi, M.S.; Haider, S.; Habib, S.R.; Altamash, S.; Zafar, M.S.; Alam, M.K. Fit Accuracy of Removable Partial Denture Frameworks Fabricated with CAD/CAM, Rapid Prototyping, and Conventional Techniques: A Systematic Review. *Biomed. Res. Int.* **2021**, *2021*, 3194433.
15. Fueki, K.; Inamochi, Y.; Wada, J.; Arai, Y.; Takaichi, A.; Murakami, N.; Ueno, T.; Wakabayashi, N. A Systematic Review of Digital Removable Partial Dentures. Part I: Clinical Evidence, Digital Impression, and Maxillomandibular Relationship Record. *J. Prosthodont. Res.* **2022**, *66*, 40–52.
16. Mai, H.Y.; Mai, H.N.; Kim, H.J.; Lee, J.; Lee, D.H. Accuracy of Removable Partial Denture Metal Frameworks Fabricated by Computer-Aided Design/Computer-Aided Manufacturing Method: A Systematic Review and Meta-Analysis. *J. Evid. Based Dent. Pract.* **2022**, *22*, 101681.
17. Muralidharan, C.; Schneider, R.L.; Kotowske, S. CAD-CAM Denture Teeth Made on Cast Metal Removable Partial Denture Frameworks. *J. Prosthet. Dent.* **2024**, *131*, 1029–1033.
18. Takebe, J. Fabrication of a Monolithic Computer-Aided Design (CAD)/Computer-Aided Manufacturing (CAM) Zirconia Crown Adapted to the Clasp of an Existing Removable Partial Denture. *Cureus* **2026**, *18*, e102028.
19. Song, S.; Ren, N.; Li, F.; Bai, S. Fully Digital Workflow for Duplicating Clasp-Retained Removable Partial Dentures Using Three-Dimensional Printing: A Clinical Report. *J. Prosthet. Dent.* **2025**, *133*, 1118–1121.

20. Tyndall, D.A.; Price, J.B.; Gaalaas, L.; Spin-Neto, R. Surveying the Landscape of Diagnostic Imaging in Dentistry's Future: Four Emerging Technologies with Promise. *J. Am. Dent. Assoc.* **2024**, *155*, 364–378.
21. Zhu, Y.; Hu, J.; Luo, B.; Yuan, Y.; Jiang, Q. Biomechanical Considerations in RPD Design: Application and Perspective of Finite Element Method in Distal Extension Removable Partial Denture Rehabilitation. *Front. Dent. Med.* **2025**, *6*, 1667504.
22. Huang, Y.; Wang, J.; Zhu, L.; Liu, L.; Gao, S. The Optimal Design and Three-Dimensional Finite Element Analysis of CAD/CAM Integrated Roach Attachment. *Heliyon* **2023**, *10*, e23283.
23. Jia-Mahasap, W.; Rungsiyakull, C.; Bumrungsiri, W.; Sirisereephap, N.; Rungsiyakull, P. Effect of Number and Location on Stress Distribution of Mini Dental Implant-Assisted Mandibular Kennedy Class I Removable Partial Denture: Three-Dimensional Finite Element Analysis. *Int. J. Dent.* **2022**, *2022*, 4825177.
24. Tun Naing, S.; Kanazawa, M.; Hada, T.; Iwaki, M.; Komagamine, Y.; Miyayasu, A.; Uehara, Y.; Minakuchi, S. In Vitro Study of the Effect of Implant Position and Attachment Type on Stress Distribution of Implant-Assisted Removable Partial Dentures. *J. Dent. Sci.* **2022**, *17*, 1697–1703.
25. Bhattacharya, D.; Maiti, S.; A A, P.; Gandhi, P.; Heboyan, A.; Zakaryan, N.; Gopalkrishna, M. Finite Element Analysis of Implant-Assisted Mandibular Distal Extension Removable Partial Denture: Evaluating Stress Distribution in Premolar Versus Molar Implant Positions—An In Silico Study. *Health Sci. Rep.* **2025**, *8*, e71360.
26. Chen, R.; Chen, Y.; Zheng, Z.; Lin, J. Effect of Geometry on Clasp Retention Force: A Finite Element Analysis Study. *BMC Oral Health* **2024**, *24*, 1522.
27. El-Tamimi, K.M.; Bayoumi, D.A.; Alshenaiber, R.; Aljulayfi, I.; Ahmed, M.M.Z.; El-Sayed, M.E. Deformation and Retentive Forces Variations of the Additively Manufactured Cobalt-Chromium and Titanium Alloys Dental Clasps. *Saudi Dent. J.* **2024**, *36*, 947–953.
28. Odaka, K.; Takano, N.; Takizawa, H.; Matsunaga, S. Probabilistic Finite Element Analysis of Fatigue Life of Additively Manufactured Clasp. *Dent. Mater. J.* **2022**, *41*, 286–294.
29. Yagci, F.; Eraslan, R.; Esim, E. Evaluation of Polyaryletherketone Materials as Post-Core Abutments for Removable Partial Dentures: A Finite Element Analysis. *Dent. Mater.* **2024**, *40*, e113–e120.
30. Srivastava, G.; Padhiary, S.K.; Schimmel, M.; Schenk, N.; Çakmak, G.; Roccuzzo, A.; Molinero-Mourelle, P. Performance of Polyetheretherketone (PEEK) versus Cobalt Chromium to Fabricate Removable Partial Denture Frameworks: A Systematic Review. *J. Prosthet. Dent.* **2025**, *134*, 652.e1–652.e10.
31. Bertotti, K.; Mwenge-Wambel, J.; Sireix, C.; Hüe, O.; Jeannin, C.; Grosogeat, B. Accurate Analysis of Titanium and PolyEtherEtherKetone Materials as an Alternative to Cobalt-Chrome Framework in Removable Partial Denture: A Systematic Review. *Dent. Mater.* **2024**, *40*, 1854–1861.
32. Silva, L.S.; Bento, V.A.A.; Brunetto, J.L.; Pesqueira, A.A. Polyetheretherketone Materials for Removable Partial Denture Frameworks: An Integrative Review. *Gen. Dent.* **2023**, *71*, 58–62.
33. Yagci, F.; Eraslan, R.; Esim, E. Evaluation of Polyaryletherketone Materials as Post-Core Abutments for Removable Partial Dentures: A Finite Element Analysis. *Dent. Mater.* **2024**, *40*, e113–e120.
34. Ediboğlu, E.; Akdeniz, S.S.; Beyler, E. Biomechanical Effects of Titanium and Carbon Fiber-Reinforced PEEK as Dental Implant Materials: A Finite Element Analysis. *Int. J. Oral Maxillofac. Implants* **2025**, *40*, 33–39.
35. Peng, P.W.; Chen, M.S.; Peng, T.Y.; Huang, P.C.; Nikawa, H.; Lee, W.F. In Vitro Study of Optimal Removable Partial Denture Clasp Design Made from Novel High Performance Polyetherketoneketone. *J. Prosthodont. Res.* **2024**, *68*, 466–473.

36. Ghazy, E.S.; Altonbary, G.Y.; Gebreel, A.; El-Daker, M.A.; Hegazy, S.A. Evaluation and Comparison of Retention and Patient Satisfaction with Milled Polyetheretherketone versus Metal Maxillary Obturators. *J. Prosthet. Dent.* **2025**, *134*, 259–267.
37. Atif, M.; Tewari, N.; Reshikesh, M.; Chanda, A.; Mathur, V.P.; Morankar, R. Methods and Applications of Finite Element Analysis in Dental Trauma Research: A Scoping Review. *Dent. Traumatol.* **2024**, *40*, 366–388.
38. Aliberti, A.; Caggiano, M.; Piscopo, M.; Gasparro, R.; Cernera, M.; Armogida, N.G.; Ausiello, P. Finite Element Analysis in Polymer-Based Adhesive Dental Restorations: A Narrative Review on Material Behavior, Methodological Validity, and Clinical Relevance. *Polymers* **2026**, *18*, 580.
39. Guo, R.; Lam, X.Y.; Zhang, L.; Li, W.; Lin, Y. Biomechanical Analysis of Miniscrew-Assisted Molar Distalization with Clear Aligners: A Three-Dimensional Finite Element Study. *Eur. J. Orthod.* **2024**, *46*, cjad077.
40. Xue, Q.; Hu, M.; Xu, M.; Zhang, X.; Wang, H.; Sun, M.; Wang, C.; He, Y. Biomechanical Analysis of Maxillary First Molar Intrusion Using 3D Printed Personalized Device Combined with Clear Aligner: A Finite Element Study and Clinical Application. *Clin. Oral Investig.* **2025**, *29*, 259.
41. Xie, B.; Chen, J.; Zhao, T.; Shen, J.; Dörsam, I.; He, Y. Three-Dimensional Finite Element Analysis of Anterior Fixed Partial Denture Supported by Implants with Different Materials. *Ann. Anat.* **2022**, *243*, 151943.
42. Revilla-León, M.; Gómez-Polo, M.; Vyas, S.; Barmak, B.A.; Gallucci, G.O.; Att, W.; Krishnamurthy, V.R. Artificial Intelligence Applications in Implant Dentistry: A Systematic Review. *J. Prosthet. Dent.* **2023**, *129*, 293–300.
43. Schierz, O.; Hirsch, C.; Krey, K.F.; Ganss, C.; Kämmerer, P.W.; Schlenz, M.A. Digital Dentistry and Its Impact on Oral Health-Related Quality of Life. *J. Evid. Based Dent. Pract.* **2024**, *24*, 101946.
44. Schwendicke, F.; Mohammad Rahimi, H.; Tichy, A. Artificial Intelligence in Prosthodontics. *Dent. Clin. North Am.* **2025**, *69*, 315–326.
45. Ali, I.E.; Tanikawa, C.; Chikai, M.; Ino, S.; Sumita, Y.; Wakabayashi, N. Applications and Performance of Artificial Intelligence Models in Removable Prosthodontics: A Literature Review. *J. Prosthodont. Res.* **2024**, *68*, 358–367.
46. Gupta, V.; Garg, A.; Tewari, N.; Srivastav, S.; Chanda, A. Development of Patient-Specific Finite Element Model for Study of Composite Dental Implants. *Biomed. Phys. Eng. Express* **2024**, *10*, 10.1088/2057-1976/ad28ce.
47. Choudhury, S.; Rana, M.; Chakraborty, A.; Majumder, S.; Roy, S.; RoyChowdhury, A.; Datta, S. Design of Patient Specific Basal Dental Implant Using Finite Element Method and Artificial Neural Network Technique. *Proc. Inst. Mech. Eng. H* **2022**, *236*, 1375–1387.
48. Roy, S.; Richert, R.; Tavares, J.M.R.S.; Lahoud, P. Editorial: Applications of Digital Twin Technology in Dentistry. *Front. Bioeng. Biotechnol.* **2025**, *13*, 1624734.