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Advancements in finite element analysis for prosthodontics

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Highlights

- This paper presents a comprehensive review of the advancements in finite element analysis (FEA) within the field of prosthodontics over the past five years.
- It examines the role of FEA in aiding the selection of restorative materials, enhancing prosthetic designs, and investigating the dynamic interactions between prostheses and natural dentition.
- Integrating FEA findings with clinical practice enhances treatment outcomes and patient satisfaction.

Abstract

Finite element analysis (FEA) is a computer-aided tool widely employed in the field of prosthodontics, offering a comprehensive understanding of biomechanical behavior and assisting in the design and evaluation of dental prostheses. By dividing a model into finite elements, FEA enables accurate predictions of stress, strain, and displacement of structures. This review summarizes recent research developments in the application of FEA across various aspects of prosthodontics, including dental implant, removable partial denture, fixed partial denture and their combinations. FEA plays a significant role in selecting restoration materials, optimizing prosthetic designs, and examining the dynamic interactions between prostheses and natural teeth. Its computational efficiency and accuracy have expanded its application potentials for preoperative planning in custom-made prosthodontics. Upon the physician's assessment of the repair requirements tailored to the individual patient's condition, FEA can be employed to evaluate the stress distribution, displacement, and other relevant outcomes associated with the proposed restoration. When integrated with clinical expertise, it facilitates assessing design feasibility, identifying necessary adjustments, and optimizing prosthetic solutions to mitigate the risk of failure. Additionally, FEA helps identify potential complications arising from long-term prosthetics use, allowing for the implementation of preventive strategies. Presenting FEA results to patients enhances their understanding of the scientific basis and rationale behind the design, thereby bolstering patient confidence in the proposed intervention. Despite its ongoing limitations, FEA underscores the importance of integrating computational findings with clinical judgment and supplementary diagnostic tools. This review emphasizes the growing role of FEA in advancing prosthodontics by offering computational analysis and design optimization, ultimately improving treatment outcomes and patient satisfaction.

Keywords: Finite element analysis, dental implant, removable partial denture, fixed denture, fixed partial denture

Introduction

Dental caries, a prevalent oral disease, can develop at any stage of life, potentially leading to tooth damage and eventual tooth loss [1]. Clinically, dental caries progression can be categorized into three stages: tooth defect, dentition defect, and edentulousness. Tooth defect refers to damaged or abnormal tooth morphology. As the condition worsens, multiple tooth extractions may become necessary, leading to a dentition defect. In severe cases, edentulousness - complete loss of teeth in the upper and (or) lower jaw, occurs. These conditions significantly impact dental aesthetics and functionality, potentially causing anxiety, diminished

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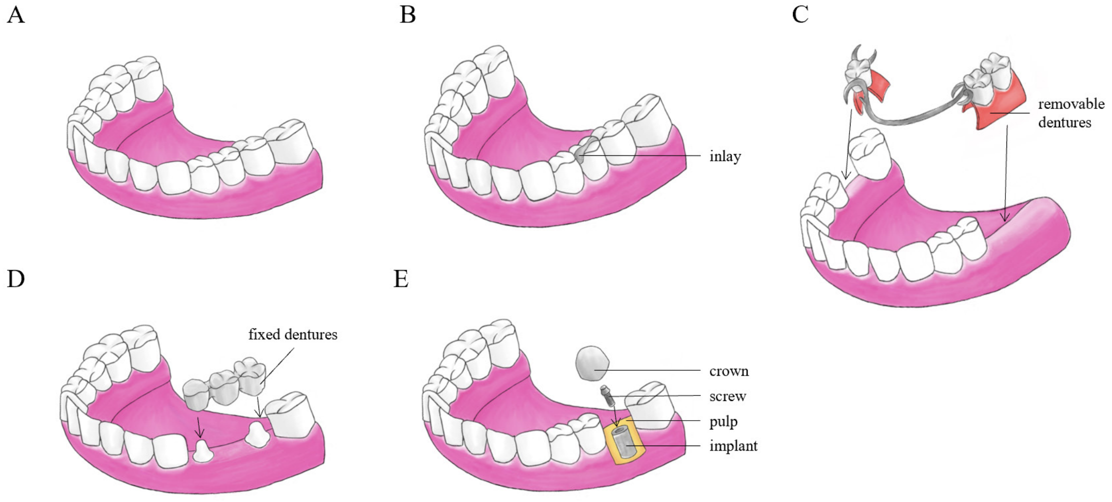

Figure 1. Healthy teeth and common treatment modalities. Schemes of (A) healthy teeth and various aspects of treatment modalities within the field of prosthodontics. Specifically, the schemes encompass: (B) inlays, with the gray area denoting the inlay component; (C) removable dentures, depicted as situated above the natural teeth; (D) fixed dentures, which are also represented in gray; and (E) dental implants, where the pulp is highlighted in yellow, alongside the incorporation of implants and screws within the dental architecture.

self-esteem, and other negative emotions that affect patients' physical and mental well-being.

Prosthodontics offers a range of treatment options tailored to varying tooth defects, including inlays, implants, removable dentures, fixed dentures, and combination treatments, as shown in **Figure 1**. Compared to onlays that sit partially above the tooth surface, inlays are completely embedded within the crown, which restore tooth shape and function while preventing further loss of tooth substance. As for dentition defects, removable partial dentures (RPDs) are commonly employed due to their wide range of applications and cost-effectiveness. However, RPDs rely on a dual support system that may compromise retention and stability, particularly with multiple missing teeth or posterior tooth loss, where rotation during chewing can affect chewing function [2, 3].

In contrast, fixed dentures, also known as fixed bridges, are securely attached to neighboring teeth or implants, providing greater stability. However, their application often requires removing more healthy tooth material, and they are more challenging to clean thoroughly, potentially leading to infection. For patients with edentulousness, traditional complete dentures, removable appliance, share similar drawbacks to RPDs [4]. Implant dentures, on the other hand, have rapidly evolved, demonstrating high success rates (89-100%) across various indications and therapies, making them a viable and increasingly popular solution [5, 6]. Furthermore, the integration of implants with other restoration methods has emerged as a new direction for prosthodontics.

Despite the availability of various treatment options, determining the most appropriate repair methods tailored to the specific requirements of each individual case remains a significant challenge. In vitro testing is generally accepted in dentistry, notwithstanding its inherent limitations concerning precision and intricacy [7]. The integration of digital technologies, such as computer-aided design (CAD) and computer-aided manufacturing, virtual reality, additive manufacturing (3D printing) and finite element analysis (FEA), is transforming the field [8-23]. Such technologies hold promises in enhancing diagnostic precision, tailoring treatments to individual needs, streamlining operational efficiency, promoting patient experiences, and fostering clinical excellence in dentistry.

Simulating the complex human biomechanical system such as bone and soft tissue is a challenging task in the medical field, and FEA emerges as an effective solution to address these complexities [24, 25]. It is a widely used numerical method that uses CAD to construct and analyze mathematical models of engineering or physical systems [25, 26]. Introduced by Courant in 1943, FEA found application in orthopedics in the 1970s, where it was used to evaluate stress and deformations in human bones under functional loading [27-29]. Since its introduction to dentistry in 1973, FEA has been extensively used to simplify complex oral systems into manageable data models [26, 30, 31]. FEA is used in dentistry for various purposes, including analyzing soft tissue changes be-

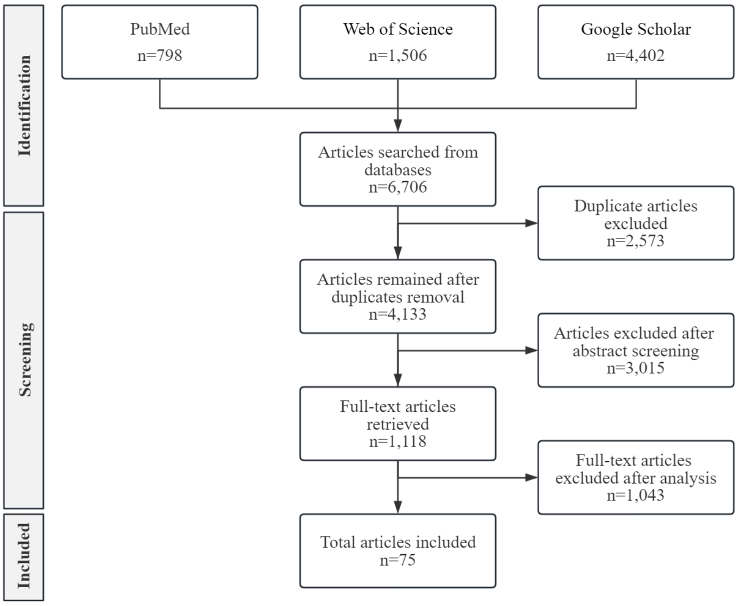

Figure 2. Review flow chart. The methodology involves utilizing specific databases and search terms to conduct an initial screening based on titles and abstracts. This is followed by a more comprehensive evaluation of the full-text content, guided by established inclusion and exclusion criteria.

fore and after operations, simulating craniofacial bone anatomy, customizing optimal surgical strategies by evaluating stress distribution and displacement in reconstruction components, and assessing bone conditions and load-carrying capacity around implants [32-36].

The aim of this review is to summarize the recent advancements in the application FEA in prosthodontics. The paper is structured as follows: Chapter 2 introduces the literature search method, establishing a foundation for the subsequent research. Chapter 3 describes the fundamental steps of FEA, offering theoretical and technical framework. Chapters 4 to 6 constitute the core of this paper, covering the application of FEA to the analysis of restorative materials, the design of restorative structures, and the analysis of the interaction between the restoration and the teeth. Finally, Chapter 7 concludes the review by summarizing current trends and proposing potential future directions in this field.

Literature search

This review systematically searched the existing literature in databases including PubMed, Web of Science, and Google Scholar, from 2019 to 2024. The search terms included “dental implant,” “removable partial denture,” “fixed denture,” “fixed partial denture,” and “finite element,” used alone or combined with Boolean operators (e.g. AND, OR). References from the identified articles were also examined to ensure a comprehensive collection. **Figure 2** shows the process of article screening. The retrieved literature was imported into EndNote to remove duplicates. Initially, a preliminary screening based on article titles was performed, selecting those explicitly referencing the specified keywords. Articles unrelated to FEA, such as purely biological research or descriptions of clinical procedures, were excluded. Subsequently, the abstracts of the selected articles were examined to ascertain the clarity of the study’s purpose and a concise summary of the main findings. Abstracts incorporating keywords pertinent to prosthodontics and presenting novel methods, models, or insights were prioritized. Following this initial screening, full-text articles were thoroughly evaluated. The assessment focused on the validity of the study design, including the development of finite element models, the appropriate application of boundary conditions and loads. Inclusion criteria stipulate that studies should be published in English, specifically address FEA in the context of prosthodontics, and provide comprehensive descriptions of the models and analyses of the results. Articles lacking adequate model validation, employing outdated methodologies, or unrelated to prosthodontics were excluded. Finally, the obtained literature was analyzed in detail.

General procedure of finite element analysis

As a computer-based approach, FEA employs mathematical models to analyze practical problems in various fields. The primary objective of FEA is not to achieve an exact result, but to offer approximate solutions that include some fundamental information, such as displacement, force, temperature. **Figure 3** presents the general analysis process of FEA. The first step is to construct an overall geometric model. This model is then divided into a finite number of small elements for generating meshes, which is termed discretization. FEA focuses on the analysis of these individual elements. Mechanical properties and material characteristics of individual elements are analyzed independently, constructing the corresponding stiffness matrix. Following this step, the mechanical properties of the entire model are calculated, allowing for the estimation of stress, strain, displacement

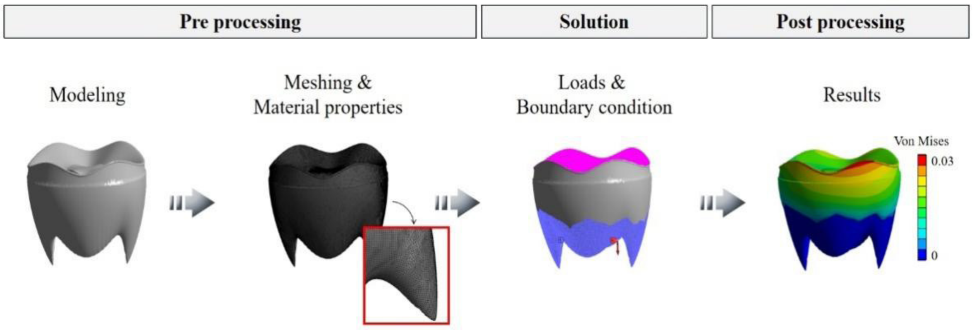

Figure 3. FEA procedure. The pre-processing phase encompasses several critical steps, including the development of a model, the creation of a mesh, and the specification of material parameters. Subsequently, appropriate load and boundary conditions are established, followed by the analysis of results utilizing finite element calculations. FEA, Finite element analysis procedure.

and other response outcomes [25, 29]. The key steps in the FEA procedure are briefly described below. For interested readers, more detailed tutorials may be found in these reviews [37-39].

Construction of geometric model

The construction of a geometric model is the first step in FEA for prosthodontics, including multiple components, such as prosthesis, bone, and tooth. The prosthesis geometry is usually based on the design data provided by manufacturers.

The bone models are categorized into simple and complex structures [25]. For simple structures, the bone is represented through an array of 2D or 3D shapes, while both cortical and trabecular components are retained. Complex structures are typically obtained using medical imaging techniques, such as intraoral scanners and cone beam computer tomography [10, 40]. FEA can be performed directly on the geometric model obtained from medical images [37]. However, the bone model to be analyzed must first be segmented, typically through image processing software like Mimics or Amira. The segmented images are then converted into finite element models using CAD tools (e.g. Geomagic, SolidWorks).

Tooth models typically consist of enamel, dentin, and pulp. The modeling process is similar to that of bone models (i.e. images are obtained through medical imaging technology, processed and modeled using CAD). In some cases, ex vivo test models are used, where a physical tooth model is created from extracted teeth [41, 42]. Alternatively, finite element models may be directly generated from existing image data [43].

Discretization and assignment of material properties

Meshing, or discretization, is a crucial step in finite element analysis. This process involves dividing the geometric model into smaller computational elements. To ensure accuracy and efficiency of the analysis, the mesh size must be sufficiently fine so that the results are independent of the mesh size. Additionally, it is important to strike a balance between geometric complexity and computational efficiency, as the choice of element type significantly influences the analysis. In 2D finite element modeling, structures are commonly divided into triangular or quadrilateral elements, while tetrahedral or hexahedral elements are typically employed in 3D modeling. Tetrahedral elements are more frequently used compared to hexahedral ones, not only due to more convenient meshing automation, but also better fitting to complex geometries [44]. Researchers often use pre-processing software, such as Hypermesh, HyperWorks, and VR Mesh Studio, to improve mesh quality and analysis productivity [42, 45-49].

To meet specific application requirements, it is necessary to assign appropriate material properties for all model components, as these properties significantly influence the accuracy of FEA results. The mechanical properties of bone, teeth, and restorative materials, such as elastic modulus, shear modulus, and Poisson's ratio, can be obtained experimentally or referenced from previous reports.

FEA simplifies the model's complexity by adjusting the quantity and nature of elements and specifying material properties to ensure precision. However, clinical validation remains essential to confirm the accuracy of the approximate outcomes [50]. Despite the inherent complexity of biological structures, models are commonly simplified with material properties often assumed to be homogeneous, isotropic and linear elastic for reducing computation time. This does not mean that important details should be left out or omitted. Oversimplification may lead to the exclusion of essential characteristics, resulting in inaccurate representation. Hence, it is imperative to achieve a delicate balance between computational efficiency and model accuracy.

To better simulate real-life scenarios, some researchers adjust material properties to better match actual conditions. For instance, Chakraborty modeled the mandible as a heterogeneous material, considering different bone conditions to evaluate the implant's biomechanical potential for promoting osseointegration at the peri-implant bone [51]. This method can simulate the implant process based on the patient's bone condition, which aids in selecting suitable implants and creating personalized treatment plans. Meanwhile, Ortiz-Puigpelat developed a methodology utilizing a nonlinear geometric model and material properties specific to the periodontal ligament to predict its mechanical response during occlusion [52]. This approach closely replicate actual clinical conditions, offering enhanced precision and reliability in FEA results, which can inform clinical assessments and therapeutic interventions.

Boundary conditions

After discretization, boundary conditions and loads should be appropriately assigned based on different experimental purposes. The boundary conditions can be fixed, free, periodic, or other types. Most studies assume that the connections between the prosthesis, abutments, and bone interfaces are tightly coupled, with nodes constrained in all directions to prevent translation or rotation. Previous studies have shown that fixed boundary conditions are commonly used to simulate tooth roots fixed in the bone when the periodontal ligament model is neglected [41, 53, 54]. This involves fixing the tooth from the enamel-cementum junction to the apical region. Additionally, masticatory forces are typically simulated by applying vertical and/or oblique loads. To simulate the actual chewing force, some studies incorporate food clumps or spherical objects on the tooth contact surface to represent food and apply loads accordingly [48, 55, 56].

Solution and analysis

The accuracy of FEA depends on the above steps. With the help of software specialized FEA, a large amount of data can be obtained for the solution of the finite element model which has been set up. After obtaining the solution, the results may be analyzed and displayed by post-processing, which involves calculating additional physical quantities (e.g. stress, strain, displacement) and visualizing the results. In the following chapters, FEA results are analyzed from three application perspectives.

Analysis of restoration materials

The selection of a restoration material significant influences the magnitude and distribution of stress in teeth [57]. Various materials are available to dentists, including zirconia, lithium disilicates, ceramics, amalgam, and resin-based composites. **Figure 4** provides a comparative illustration of clinically used restorative materials based on relevant literature [58-61]. However, selecting the most suitable material for a given situation can be challenging [49]. FEA enables the creation of restoration models using different materials, simulate bite forces with varied directions and magnitudes, and evaluates the resulting stress and strain under maximum load conditions (**Table 1**) [43]. The primary focus of material analysis is to evaluate the modulus of elasticity (MOE).

FEA studies demonstrate that significant discrepancies between the MOE of dental restorative materials and dental tissues can lead to extremely large stress values. Therefore, a comparable MOE between materials and dental tissues reduces stress transmitted to the dental tissues [43]. Kim et al. utilized FEA to analyze optimal materials for mitigating residual crack propagation, finding that materials with lower MOE exhibited deformation due to stress absorption, while those with higher MOE exerted increased stress and stress concentration in the teeth, potentially enhancing aesthetic quality and fracture resistance [48]. Darwich et al. came to the similar conclusion when evaluating the material of the inner crown [40]. Therefore, it is recommended to use hard materials with high MOE to reduce the displacement of the tooth structure.

FEA can also be applied to study the fatigue properties of restoration materials. As high stress or stress concentration can potentially lead to cracks, Kim et al. evaluated crack propagation by assessing residual stress beyond the lower edge of the crack surface after treatment, identifying gold crown combined with resin filling as the most effective treatment method [48]. Demirel et al. compared the fatigue properties of various ceramic materials by simulating crack generation and propagation in repair materials through FEA, and found that polymer-infiltrated ceramic networks exhibited greater brittleness due to their lower MOE com-

Table 1. Material types and material properties analyzed in the different studies

Applications	Materials	Properties		Load direction & magnitude	Conclusion	Ref.
		MOE (MPa)	Poisson's ratio			
Endocrown	Translucent zirconia	210,000	0.307	Constant load: 600 N Direction: -Axial load: perpendicular to the occlusal surface of the crown -Oblique load: tilted by 45° with respect to the tooth axis	Translucent zirconia is considered the optimal material for internal crowns to preserve the dental restoration complex. Both lithium disilicate glass ceramic and zirconia-reinforced lithium silicate ceramic are appropriate materials to produce internal crowns, but resin nanoceramics may not be the most suitable option.	[40]
	Zirconia-reinforced lithium silicate ceramic	102,900	0.208			
	Lithium disilicate glass ceramic	83,000	0.210			
	Polymer-infiltrated network ceramic	30,000	0.230			
	Resin nanoceramic	12,700	0.470			
Inlay, Onlay, Overlay	Lithium disilicates (LS)	98,000	0.230	Constant load: 600 N Direction: perpendicular to the occlusal surface of the crown	LS exhibits superior properties relative to PICN materials.	[41]
	Polymer-infiltrated ceramic network (PICN)	35,000	0.230			
Inlay	Direct composite resin (Filtek Z350)	9,800	0.250	Constant load: 1,000 N Sliding-type contact: the contact points of a 6 mm diameter sphere* placed in the fovea	A gold crown filled internally with resin is an advantageous method to prevent further crack propagation in cracked teeth.	[48]
	Indirect composite resin (Tescera ATL)	14,200	0.250			
	Ceramic (Emax)	94,100	0.250			
	Gold	85,000	0.250			
RPD	Zirconia	210,000	0.300	Constant load: 100 N Direction: perpendicular to the bottom surface of the small connector	Zirconia occlusal rests, derived from conventional occlusal rest designs, are regarded as occlusal supports capable of enduring repetitive masticatory forces. The limited fatigue resistance of PEEK may render it unsuitable for extended clinical use as a dental scaffold material.	[97]
	Polyether-ether-ketone (PEEK)	4,100	0.400			
RPD	Zirconia (3Y-TZP)	200,000	0.300	Constant load: 600 N perpendicular to the occlusal surface of the crown	PEEK demonstrates enhanced biomechanical characteristics when utilized as the primary crown within a double-crown attachment system, but its effectiveness still needs additional validation.	[98]
	Titanium (Ti-6Al-4V)	110,000	0.300			
	CoCr	220,000	0.300			
	PEEK	5,100	0.400			
FPD	Zirconia	220,000	0.300	Constant load: 300 N Direction: perpendicular to the occlusal surface of the crown	Zirconia material can be utilized to fabricate implants-assisted FPD.	[50]
	Titanium	110,000	0.300			
FPD	Zirconia	210,000	0.260	Constant load: 1,000 N Direction: -Axial load: three vertical force vectors -Oblique load: tilted by 60° with respect to the tooth axis	The first principal stress at the inlay fixator and the connector is affected differently by the stiffness variation of the support structure.	[99]

Note: *A 6 mm diameter sphere was used to simulate food clump.

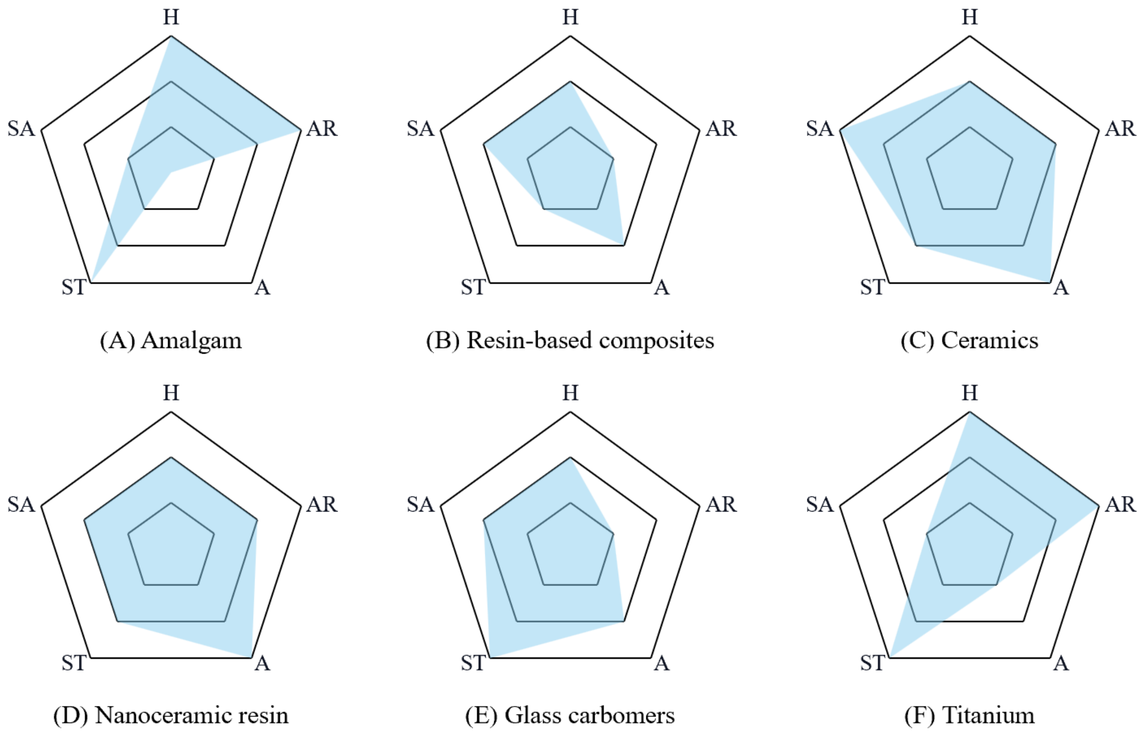

Figure 4. Comparison of performance of restoration materials. Six commonly used repair materials, i.e. (A) amalgam, (B) resin-based composites, (C) ceramics, (D) nanoceramic resin, (E) glass carbomers and (F) titanium, are evaluated relative to hardness (H), abrasion resistance (AR), aesthetics (A), service time (ST) and scope of application (SA).

pared to lithium disilicate glass ceramic [41].

Zirconia fixed partial dentures (FPDs) are known for their exceptional fracture resistance and superior fatigue properties compared to other dental ceramics, as demonstrated by recent FEA studies [50]. The fatigue resistance of zirconia FPDs is significantly higher than that of lithium disilicates FPDs, making them particularly suitable for cases involving molar replacement [62]. It is worth noting that suitable core materials can help reduce the fracture risk of zirconia FPDs. Canipaner et al. compared sound dentin, resin composite cores, and metallic cores, finding that while resin composite cores are less strong than metal cores, their flexibility helps disperse stress, thereby reducing fracture risk [63]. This underscores the importance of prosthesis design when selecting zirconia materials. However, Ceddia et al. recently compared crowns made of ceramic and zirconia with natural enamel to assess their mechanical properties under different loading conditions [64]. Vertical, oblique (45°), and horizontal loads were applied to simulate chewing. While ceramic crowns exhibited inferior mechanical properties and were more prone to fracture or fragmentation, zirconia crowns displayed higher stress levels under vertical and horizontal loads. This suggests that zirconia crowns may not be ideal for patients with oral dysfunction. Therefore, clinicians should choose appropriate materials according to the patient's specific dental condition.

In addition to repetitive functional loading, human teeth are subject to thermal stress from lifelong temperature fluctuations [65]. FEA simulations have shown that both hot and cold loads result in elevated stress levels in the inlays.

Structural designs of the dental prosthesis

Figure 5 shows the general procedure of dental restoration, from the beginning of clinical diagnosis to the final prosthesis installation, including material selection and shape. The effectiveness of restorative treatments depends not only on the properties of the restorative material but also on the design of the prosthesis structures. FEA provides a virtual platform to simulate various design iterations, enabling the identification of potential issues without the need for physical prototype.

Proper cavity designs are essential for inlays, as they can make use of residual tooth tissue while ensuring adequate fracture resistance and retention force, thereby reducing the risk of fracture. Cheng et al. used EFA to demonstrate that a concave design significantly improves the fracture resistance of ceramic inlays compared to flat designs [45]. Similarly, Babaei

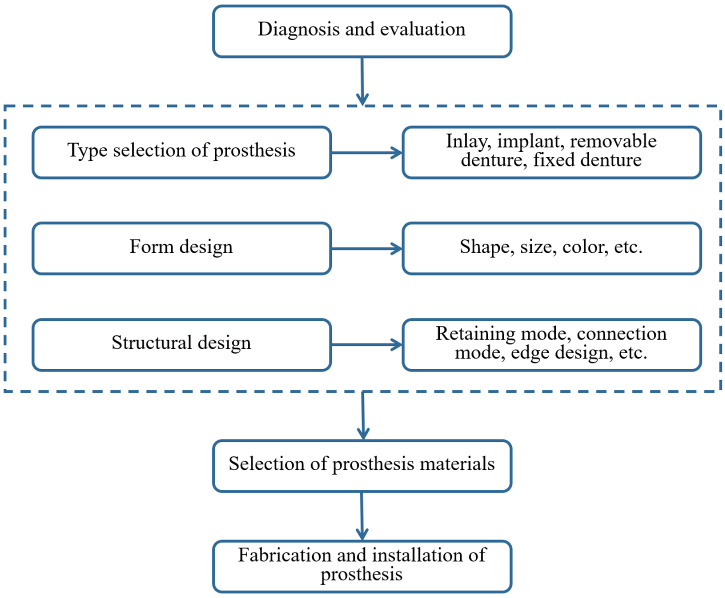

Figure 5. General procedures for dental restoration. Following the dentist's diagnosis, the selection of the prosthesis is determined based on the patient's specific condition. Subsequently, the design of the shape and structure is undertaken, after which the most suitable material for the fabrication and installation of the prosthesis is chosen.

et al. analyzed the effects of occlusal cavity depth and internal cavity angle (α) on the biomechanical stability of treated molars [7]. They demonstrated that as the occlusal cavity depth increases, the pressure level of the restoration also increases, resulting in reduced fracture resistance. Conversely, increasing α and reducing occlusal cavity depth lowers the pressure levels within the restoration, thereby improving stability and fracture resistance. This conclusion is consistent with the results reported by She et al. [66].

The design of the pier abutment and connector plays a crucial role in determining repair effectiveness and service life of FPD [67, 68]. Recent FEA studies have shown that the connector volume is a key factor affecting the maximum principal stress of dentures [10]. Smaller connector volumes result in higher maximum equivalent stress. Additionally, FEA has demonstrated that the area surrounding the connector experiences the highest stress levels, regardless of the design or material used [11, 12]. To compensate for differences in movement between implants and natural teeth, both rigid and non-rigid connectors can be utilized depending on the specific cases [69]. FEA results indicate that the non-rigid connectors reduce stress concentration in the bone surrounding the implant but increase stress levels in the alveolar bone [70]. In the design of a 5-element FPD, non-rigid connector was found to be more suitable [67, 68]. However, Naguib et al. observed through FEA that rigid connectors generate lower stress values than non-rigid connectors [69]. Therefore, when designing a three-element FPD, it is recommended to consider the optimal implant diameter and length and choose a rigid connection design to minimize stress on both the prosthesis and supporting bone.

Numerous studies have investigated the application of FEA in implant dentures. As for implants, Falcinelli et al. provided a comprehensive review of FEA application in implant dentures over the past 20 years [25]. Most studies focused on evaluating stress distribution in implants and surrounding bone, demonstrating that factors such as implant geometry, connection design, implant material, and properties of the bone-implant interface significantly influence the stress field. Key factors affecting load transfer and stress distribution include diameter of the implant, the length of the bone-implant interface, and the spacing, shape, and depth of the threads. The dimensions of an implant, specifically its diameter and length, directly impacts the stress distribution in the surrounding bone [71]. Increasing implant diameter reduces bone stress near the implant [72]. By optimizing the geometric configuration of the implant, it is possible to mitigate bone resorption around the implant, thereby enhancing both implant stability and the likelihood of long-term success. Furthermore, design of the implant-abutment connection also plays a critical role in stress transfer mechanisms, influencing stress distribution at the interface between the bone and the implant. An appropriately designed connection can alleviate stress concentration, lowering the risk of implant loosening and failure [73, 74]. Additionally, implant material selection, as discussed in Chapter 4, is vital for achieving optimal biocompatibility and mechanical compatibility with adjacent bone tissue. Selecting materials with an appropriate MOE minimizes bone resorption and mitigates implant failure risks. The nature of the implant connection exerts a more significant influence on the stress experienced by the implant and abutment than the diameter of the components. Tissue-level connections demonstrate a more advantageous stress distribution compared to bone-level connections. Lee recommends tissue-level connections for patients with low-density cancellous bone [75]. Additionally, bone strain is influenced by bone mineral density, with higher bone mineral density levels correlate with reduced stress on both the bone and the implants [76].

Implant-supported dentures are a reliable and predictable treatment option with high survival rates and long-term stability, owing to the advancements and widespread adoption of implant technology [77]. Studies using FEA have demonstrated consistent results for implant-supported dentures. For instance, Güzelce et al. compared the stress effects of various implant types for overdentures on supporting bone, implants, and frame materials under masticatory forces [78]. The study revealed that overdentures supported by conventional implants are more stable than those supported by micro-implants.

It is worth noting that traditional implant-supported fixed complete dentures typically require 6-8 implants and involve a long recovery time. The concept of All-on-4®, a clinical plan for implant-supported and immediate restoration of edentulous jaws proposed by Maló, has been extensively studied in clinical practice [79-84]. Similar to findings in implant dentures and implant-supported FPDs, FEA analyses of the All-on-4® system indicate that modifying the implant design in complete fixed denture supported by four implants has minimal impact on bone stress and strain. Therefore, altering the implant design may have little effect on implant bone remodeling.

Analysis of the interaction between the restoration and the tooth

Despite the material selection and structural design, the long-term stability and success of dental restorations also rely on the interaction between the prosthesis and the tooth. FEA can accurately simulate this interaction, delivering objective and comprehensive evaluations of prosthesis performance that are invaluable for clinical decision-making. By simulating forces under various conditions, FEA examines how the prosthesis influences stress distribution, displacement, and other parameters in the tooth. This analytical approach aids in uncovering the inherent principles governing the prosthesis - tooth interaction and elucidating the reciprocal mechanisms.

The integrity of the adhesive interface is important for the success of inlay repairs [85]. Previous studies have shown that the thickness of the adhesive layer affects the stress distribution and wear, though the ideal thickness remains debated [56]. Restorative materials also play a crucial role in the stress distribution and damage degree at the enamel-inlay bonding interface. He et al. conducted FEA to analyze the stress distribution of the inner crown and cement layers using different restoration materials and resin cements [55]. Their findings revealed that higher material hardness reduced stress on the cement layer because high-MOE materials concentrated the stress within themselves, thereby lowering peak stress on the cement layer. Therefore, high-MOE material is beneficial for bonding. Ceramic inlays bear the stress primarily on the ceramic structure, minimizing damage to the enamel. In contrast, resin composite inlays release shrinkage stress at the interface with the tooth structure, promoting crack propagation towards the inner enamel. Therefore, ceramic inlays offer superior protection residual dental tissue compared to resin composite inlays, which is consistent with the findings in Chapter 4.

Implant-assisted RPDs (IARPDs) enhance retention force and stability through both direct effects of the implant and indirect effects on the bone. Additionally, they also help maintain bone levels around the implant, particularly in cases of posterior tooth loss [86]. In a review of FEA, Ichikawa et al. analyzed the strain distribution across the metal frame, tooth root, and other components, focusing on the impact of implant positioning on the load distribution of IARPDs supporting elements [87]. Their results indicate that the position of implants in IARPDs can affect the load distribution of abutment teeth and implants. Implant support and/or retention in IARPDs can prevent wobble motion along the rotation axis of the prosthesis, thereby reducing the risk of abutment teeth loss. Comparative studies between in vitro experiments and FEA highlight that FEA can simulate not only vertical loads but also tilted or horizontal loads, offering more accurate experimental results that closely mimic real bite force and masticatory force.

For fixed bridges, the distribution of stress is highly dependent on the number and placement of implants. FEA studies has shown that optimal bone stress distribution and prevention of bone resorption caused by stress concentration can be achieved by using at least three implants to support a four-unit implant-supported FPD [47, 77, 80]. FEA has shown that the highest stress concentration occurs in the contact area between the abutment and implant, regardless of the abutment type [88]. Naguib et al. found through FEA that using implants with a larger width is more conducive to stress propagation, aligning with prior FEA research on implant dentures [71, 89]. Furthermore, FEA also identified a proportional relationship between implant length and stress: increasing the length of the distal implant while maintaining a fixed diameter may result in higher torque and stress [71].

Researchers have increasingly focused on tilted implants in complete denture restoration. FEA was used to evaluate the maximum von-Mises stress experienced by the implant and the adjacent cortical bone. Studies have shown that stress and strain exerted on the surrounding bone tissue are significantly influenced by the positioning of the load, whereas the implant's design has minimal impact [35]. Elevated bone stresses and strains were observed when the load was positioned near the tilted posterior implant. Similarly, Ibrahim et al. utilized FEA in their investigation and confirmed that stress levels increased with the angle of posterior implant tilt, suggesting that optimizing the implant's tilt angle can mitigate deformation and enhance performance [90].

While most FEA studies focus on mechanical factors, they may not fully account for biological responses, such as bone remodeling and tissue healing, which are critical to clinical outcomes. FEA provides valuable insights into the influence of prosthetic design on the healing of adjacent tissues. Implant designs that induce localized stress concentrations may disrupt the normal healing process, potentially delaying or impairing recovery. The adaptation of bone tissue in response to mechanical loading, known as bone remodeling, is a critical determinant of the long-term stability of implants. FEA models can incorporate bone remodeling processes to forecast alterations in bone density surrounding the implant and assess the long-term effects of prosthetic design. For instance, Poovarodom developed a bone remodeling algorithm based on FEA to simulate changes in bone density in response to mechanical stimulation, such as bite force [74]. Strain induced by mechanical loading influences bone density changes over time. By implementing a 12-month bone remodeling algorithm, the study optimized key parameters, including implant placement depth, abutment taper, and gingival height of the titanium abutment. Findings indicated that both implant placement depth and taper significantly affect bone remodeling, with the optimized model improving bone density uniformity. Rajaeirad employed the same theoretical framework of bone remodeling algorithms to forecast the impact of functionally graded materials on the process of bone remodeling [91]. FEA results indicated that the bone density and mechanical properties of titanium-hydroxyapatite (Ti-HAP) implants were influenced by the volume fraction of hydroxyapatite within functionally graded materials, consequently enhancing osseointegration and remodeling.

Current trends and future directions

FEA continues to play a pivotal role in advancing biomechanical research in prosthodontics and offers substantial potential for clinical application. While FEA is currently employed in prosthetics under static and ideal conditions, it has significant advantages in scientific research, including short experimental duration, good repeatability, and the ability to test a wide range of complex working conditions without causing damage. These attributes make it an invaluable predictive tool for clinical performance [85].

In clinical practice, the selection of an appropriate repair method should consider the patient's specific needs, oral condition, anticipated outcomes, and financial resources. FEA aids clinicians by providing critical insights into the properties of various materials and techniques, thereby facilitating more informed clinical decision-making. Inlays are frequently employed for small to medium-sized defects in posterior teeth, particularly when the remaining tooth structure is sufficiently robust to support the restoration [43, 85]. RPDs are indicated in scenarios involving multiple missing teeth, particularly when fixed prostheses or implants are not financially viable [92]. RPDs are relatively easy to clean and maintain and effectively restore functionality [2]. Nevertheless, their stability and comfort are generally inferior to other options and they may exert stress on adjacent natural teeth and surrounding soft tissues [2, 93]. FPDs are ideal for the restoration of one or more adjacent missing teeth, particularly in cases where the neighboring teeth are in good health [77]. They offer excellent stability, comfort, and functional and aesthetic outcomes resembling natural dentition. However, the preparation often involves the removal of a substantial amount of dental tissue from supporting teeth [94]. Implants are ideal for the restoration of one or more missing teeth, particularly for patients seeking a restoration that closely resembles natural dentition. They offer optimal stability and support, while also preserving alveolar bone structure without relying on adjacent teeth. However, implants are cost-intensive and may require an extended treatment timeline [90].

In terms of biomechanical properties, dental implants generally outperform other restorative methods, with fixed dentures ranking second and removable dentures exhibiting the least favorable characteristics. Implants exhibit the highest rates of survival and success, followed by fixed dentures, whereas removable dentures may compromise long-term outcomes due to various factors, including inadequate stability and challenges in maintenance. While removable dentures are the most economical option, fixed dentures and inlays follow, with implants representing the most expensive but delivering superior functional and aesthetic results.

Continuous technological innovation have enabled the combination of various restorative methods. For example, inlay-retained FPD provides a viable alternative for patients who decline implant treatment or traditional FPD due to aesthetic or other reasons [95]. The design of the bridge and connector is critical in such cases. FEA focuses on examining the stress levels and fracture resistance of bridges. For single missing tooth, a two-element resin-bonded FPD offers a feasible and minimally invasive treatment option [42]. Dental implant FPD is also a feasible and predictable treatment [69]. Additionally, for patients who have undergone root canal treatment, the use of internal crowns can help retain more tissue and reduce the risk of FPD fracture or debonding failure [9]. A hybrid prosthesis known as a fixed- removable denture combines a fixed component attached to abutment teeth with a removable component. Retention between the two is achieved through mechanical mechanisms, including friction, spring force, locking force, or magnetic retainers. Future research in FEA can focus on combined restoration technology. Simulation analysis can provide valuable insights into optimizing clinical strategies to meet aesthetic requirements while minimizing patient discomfort.

Nonetheless, there are notable limitations in the application of FEA to clinical practices. The accuracy of predictive FEA depends on various factors, including the geometric details of the object, boundary conditions, loads, and material properties [29]. FEA is frequently employed to model and simplify intricate biological systems, including the mechanical behavior of bone structures at both microscopic and macroscopic levels, the nonlinear characteristics of soft tissues, and the interactions between prosthetic materials and host tissues. This modeling process abstracts the actual biological environment, aiming to capture the primary mechanical features and response behaviors of the system through numerical calculations. When studying oral structures, it is also crucial to consider their deformation dynamics. Existing computer simulations often fall short of fully capturing the complexity of human biological behaviors. Most FEA studies assume that the properties of bone, teeth, and restoration materials are homogeneous, isotropic, and linearly elastic [40, 41, 88]. As stated in Section 3.2, while these assumptions enable reasonably accurate FEA results, clinical validation remains essential to ensure their applicability in real-world scenarios.

When developing FEA models, simplifying material properties is an essential step. Given the variety and complexity of biomaterials—such as the heterogeneity of bone, the viscoelastic nature of soft tissue, and the varying mechanical properties of prosthetic materials—models typically rely on average or idealized values for these properties. While this approach simplifies calculations, it may not accurately represent the true variability of material properties in clinical settings, particularly when accounting for individual differences, disease conditions, or age-related changes. Additionally, accurately simulating the biological characteristics of the occlusion process also presents challenges [96]. Loads settings in FEA are generally simplified to a single force, with only vertical or oblique load directions, fixed boundary conditions, and without considering the influence of multi-point forces. These limitations also do not invalidate the value of FEA as a predictive tool [50]. These limitations emphasize the necessity of thoughtful evaluation when using FEA in clinical scenarios, underscoring the significance of integrating FEA findings with clinical expertise and additional diagnostic methods. Further laboratory and clinical studies, including in vitro studies and long-term follow-ups, are necessary to validate the outcomes suggested by FEA [96]. For example, Ye et al. conducted a long-term follow-up study to assess the individual cases analyzed through FEA [47]. The findings showed no significant reduction in bone level or bone resorption around the implants, indicating that the implant design scheme was satisfactory in terms of function and denture stability.

The purpose of FEA is to provide dentists with an efficient tool for mechanical analysis and a reliable theoretical basis for studying the mechanical properties of restorations. In the future, developing new methods for the automatic generation and analysis of finite element models, potentially leveraging machine learning, will be essential for expanding its practical applications. In clinical practice, such advancements must focus on speed, high automation, and the ability to deliver accurate reference indices tailored to individual patient needs.

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