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BIOMIMETICS IN PROSTHODONTICS: COMPUTATIONAL TOOLS, NATURAL BIOMATERIALS, AND TRANSPLANTATION STRATEGIES FOR ADVANCED ORAL REHABILITATION

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ABSTRACT Biomimetics has emerged as a transformative concept in contemporary prosthodontics, emphasizing the restoration of biological form and function rather than the mere replacement of missing structures. Inspired by the hierarchical organization and adaptive mechanisms of natural tissues, biomimetic approaches aim to reproduce the structural, mechanical, esthetic, and functional characteristics of the dentition and its supporting tissues. Recent advances in digital technologies, regenerative biomaterials, tissue engineering, and biological tooth replacement have expanded the scope of prosthodontic rehabilitation and facilitated the development of patient-specific treatment strategies. Computational biomimetics integrates biological principles with computer-aided design and manufacturing systems to optimize morphology, stress distribution, and functional adaptation of restorations. Simultaneously, naturally derived biomaterials such as collagen, chitosan, hyaluronic acid, silk fibroin, and biodegradable polymers have demonstrated considerable potential in tissue engineering owing to their biocompatibility and extracellular matrix-mimicking properties. Biological tooth replacement through autotransplantation and homotransplantation represents another promising application of biomimetic principles by preserving periodontal ligament vitality and proprioceptive mechanisms. This review critically evaluates current developments in computational biomimetics, natural biomaterials, regenerative prosthodontics, and transplantation strategies. Furthermore, the clinical applications, limitations, and future perspectives of biomimetic rehabilitation are discussed. The convergence of artificial intelligence, regenerative medicine, and advanced manufacturing technologies is expected to further revolutionize prosthodontic treatment by enabling biologically integrated and functionally optimized rehabilitation. Biomimetics therefore represents a paradigm shift that may redefine the future of prosthodontics by promoting preservation, regeneration, and personalized oral rehabilitation.

KEYWORDS : Biomimetics, Prosthodontics, CAD/CAM, Tissue Engineering, Regenerative Dentistry, Tooth Transplantation

INTRODUCTION

Contemporary prosthodontics has evolved from a discipline primarily concerned with replacing missing teeth to one focused on restoring biological function and preserving the integrity of oral tissues. Although conventional restorative materials and prosthetic techniques have significantly improved over the past few decades, they often fail to replicate the complex structural organization and dynamic biomechanical behavior exhibited by natural teeth and supporting tissues. Consequently, there has been an increasing emphasis on biologically inspired approaches that seek to emulate the properties and functions of natural tissues rather than merely substitute them[1].

Biomimetics, derived from the Greek words *bios* (life) and *mimesis* (imitation), refers to the application of principles observed in biological systems to engineering and clinical sciences[2]. Since its introduction, biomimetics has influenced several disciplines, including aerospace engineering, robotics, material science, and medicine. In dentistry, biomimetic principles are directed toward preserving healthy tissues and reproducing the structural, mechanical, and esthetic characteristics of the natural dentition. Instead of relying solely on mechanical retention and replacement strategies, biomimetic dentistry seeks to restore the tooth as a functional biomechanical complex capable of distributing occlusal stresses in a physiological manner[1,2].

Natural teeth possess a highly organized hierarchical structure composed of enamel, dentin, cementum, periodontal ligament, and alveolar bone. These tissues function synergistically to withstand masticatory forces while maintaining proprioception and tissue homeostasis. Enamel provides exceptional hardness and wear resistance, whereas dentin contributes resilience and shock absorption. The periodontal ligament acts as a viscoelastic interface that facilitates load transmission and sensory feedback. Replicating these sophisticated interactions using artificial materials remains one of the greatest challenges in prosthodontics[3].

Recent developments in digital dentistry have expanded the applications of biomimetic concepts in prosthodontic rehabilitation. Computer-aided design and manufacturing (CAD/CAM), finite element analysis, and artificial intelligence enable the fabrication of restorations that more closely reproduce natural morphology and biomechanical behavior[3,9]. Simultaneously, advances in material science have led to the development of bioactive and naturally derived materials capable of mimicking extracellular matrix architecture and promoting tissue regeneration[4].

The emergence of regenerative medicine has further broadened the scope of biomimetics. Biomaterials, stem-cell-based therapies, and scaffold technologies are increasingly being investigated for alveolar bone regeneration, soft tissue reconstruction, and implant site development[4,6]. In addition, biologic tooth replacement through autotransplantation and homotransplantation preserves periodontal ligament vitality and proprioception, thereby representing one of the most authentic examples of biomimetic rehabilitation[5].

The integration of computational sciences, tissue engineering, and biologically inspired materials has established biomimetics as a cornerstone of modern prosthodontics. Therefore, the aim of this review is to critically evaluate recent advances in computational biomimetics, natural biomaterials, regenerative prosthodontics, and transplantation strategies and to discuss their clinical applications, limitations, and future perspectives in oral rehabilitation.

MATERIALS AND METHODS

A narrative review of the literature was performed to evaluate contemporary applications of biomimetics in prosthodontics. Electronic databases including PubMed, Scopus, and Google Scholar were searched for articles related to computational biomimetics, biomimetic materials, regenerative prosthodontics, tissue engineering, and biological tooth transplantation. Keywords used included *biomimetics in prosthodontics*, *bioinspired design*, *CAD/CAM dentistry*, *tissue engineering*, *natural biomaterials*, and *tooth autotransplantation*. Landmark studies by Kruiper et al., Liu et al., and Yang and Chang served as the primary sources for this review[3–5]. Additional references were selected based on scientific relevance, methodological quality, and significance to clinical prosthodontics. An interdisciplinary approach was adopted to integrate developments from engineering, material science, regenerative medicine, and prosthodontics.

DISCUSSION

Computational Biomimetics in Prosthodontic Design

Digital dentistry has transformed prosthodontic diagnosis, treatment planning, and prosthesis fabrication. However, the use of digital technology alone does not make a restoration biomimetic. A restoration becomes biomimetic when its design attempts to reproduce the form, function, mechanical behavior, esthetics, and biological compatibility of the natural oral structures it replaces. Computational biomimetics therefore acts as an interface between biological principles and digital prosthodontic workflows.

In natural dentition, morphology and function are closely interrelated. The form of cusps, fossae, marginal ridges, embrasures, proximal contacts, and occlusal surfaces reflects the functional requirements of mastication, speech, esthetics, and force transmission. Conventional prosthodontic design often depends on standardized tooth libraries or geometric templates, which may reproduce external form but may not fully simulate the adaptive behavior of natural tissues. Computational biomimetics addresses this limitation by incorporating biologically inspired design principles into computer-aided design and manufacturing systems. Kruiper et al. emphasized that computer-aided biomimetics should not merely copy natural shapes, but should interpret the underlying functional principles of biological structures and translate them into design solutions.[3]

Natural teeth function as complex biomechanical units. Enamel provides hardness and wear resistance, dentin contributes resilience and shock absorption, and the periodontal ligament modifies load transmission through physiological mobility and proprioception. Biomimetic CAD/CAM design therefore extends beyond simple reproduction of external anatomy. It incorporates patient-specific occlusal schemes, antagonist relationships, functional movements, and stress distribution patterns. This approach is particularly useful in crowns, fixed partial dentures, implant-supported prostheses, full-mouth rehabilitation, and maxillofacial prostheses, where inappropriate force distribution may compromise long-term success.[9]

Finite element analysis further strengthens biomimetic prosthodontic design by allowing simulation of stress distribution within teeth, restorations, implants, and supporting bone. It helps identify areas of stress concentration and guides modifications in restoration contour, connector dimensions, implant positioning, occlusal morphology, and material selection. Bio-inspired cellular and lattice-like structures have shown potential for improving mechanical efficiency while reducing material bulk, particularly in implant prosthodontics and maxillofacial rehabilitation, where strength, weight, fit, and tissue compatibility are equally important.[10]

Artificial intelligence and machine learning may further enhance computational biomimetics by analyzing large datasets, identifying morphological patterns, assisting in diagnosis, and supporting individualized restoration planning. In prosthodontics, AI may contribute to restoration design, implant planning, occlusal analysis, and prediction of long-term biomechanical performance.[16] Nevertheless, these technologies should be considered adjuncts to clinical judgment rather than substitutes for prosthodontic expertise.
Overall, computational biomimetics has shifted prosthodontic design from simple digital replication toward biologically informed rehabilitation. By combining CAD/CAM systems, finite element analysis, bio-inspired structural design, and artificial intelligence, clinicians may develop restorations that more closely approximate the mechanical behavior, functional harmony, and esthetic integration of natural dentition.

Biomimetic Materials and Tissue Engineering

The success of prosthodontic rehabilitation depends not only on replacing missing teeth but also on restoring and maintaining the supporting hard and soft tissues. Tooth loss is frequently followed by alveolar ridge resorption, soft tissue collapse, reduced prosthetic support, and compromised esthetics. Conventional grafting procedures may restore tissue volume, but they do not always reproduce the biological complexity of native tissues. Biomimetic materials and tissue engineering aim to overcome this limitation by creating biologically active environments that support regeneration rather than passive repair.

The extracellular matrix provides the natural framework for cell attachment, migration, proliferation, and differentiation. It also regulates tissue remodeling through biochemical and mechanical signals. Biomimetic biomaterials attempt to reproduce these extracellular matrix-like features. Liu et al. highlighted that natural biomaterials are valuable in tissue engineering because they possess biological recognition sites, favorable degradation behavior, and microstructural features that support cell-material interaction.[4] In prosthodontics, such materials have applications in guided bone regeneration, ridge augmentation, sinus floor elevation, peri-implant tissue reconstruction, and maxillofacial rehabilitation.

Collagen remains one of the most commonly used natural biomaterials because it is a major component of connective tissue, bone, dentin, periodontal ligament, and gingiva. Its biocompatibility, biodegradability, and ability to support cellular attachment make it suitable for regenerative procedures. In clinical prosthodontics, collagen membranes are used in guided bone regeneration and guided tissue regeneration to maintain space, exclude unwanted soft tissue invasion, and support bone formation. Collagen matrices are also useful for peri-implant soft tissue augmentation, especially where stable mucosal contours and esthetics are required.[6]

Chitosan is another important natural polymer with regenerative potential. It demonstrates biodegradability, biocompatibility, hemostatic activity, and antimicrobial properties. Owing to its similarity to glycosaminoglycans, chitosan can imitate certain extracellular matrix characteristics. Chitosan-based scaffolds may support cell adhesion and serve as carriers for growth factors, drugs, or bioactive molecules. Huang et al. demonstrated the usefulness of chitosan-gelatin scaffolds in tissue engineering, supporting their role as biologically favorable matrices.[14] In prosthodontics, chitosan-based materials may be useful in periodontal regeneration, implant surface modification, wound healing, and scaffold-based bone repair.

Hyaluronic acid is a naturally occurring glycosaminoglycan involved in tissue hydration, cell migration, wound healing, and extracellular matrix organization. Its viscoelasticity and biological activity make it useful in regenerative procedures. In oral rehabilitation, hyaluronic acid-based materials may support peri-implant soft tissue healing and contribute to bone regeneration when combined with appropriate scaffolds or growth factors. Its ability to promote angiogenesis and cellular migration is particularly important in areas where vascularization is essential for successful healing.[4]

Hydrogels are significant in biomimetic tissue engineering because their high water content and three-dimensional structure resemble the extracellular matrix. Alginate hydrogels are biocompatible and easily modified, making them useful for cell encapsulation, drug delivery, and scaffold fabrication. Lee and Mooney described the biomedical utility of alginate because of its gentle gelation behavior and tunable properties.[12] Burdick and Murphy further emphasized the development of dynamic hydrogels that respond to biological stimuli.[11] Such systems may allow controlled release of growth factors, improved vascularization, and more predictable regenerative responses in oral and maxillofacial tissues.

Silk fibroin is a protein-based biomaterial known for mechanical strength, slow degradation, and biocompatibility. These characteristics make it suitable for scaffold fabrication in tissues requiring both biological compatibility and structural stability. Meinel et al. demonstrated that silk protein scaffolds can support mesenchymal stem cells in tissue engineering.[13] In prosthodontics, silk fibroin may be useful in bone regeneration, maxillofacial reconstruction, and load-bearing scaffold systems.

Biodegradable polymers such as polycaprolactone and polyhydroxyalkanoates also contribute to biomimetic tissue engineering. Polycaprolactone has gained renewed interest because of its controlled degradation, mechanical stability, and suitability for three-dimensional scaffold fabrication. Woodruff and Hutmacher highlighted its importance in modern biomedical applications.[7] These polymers may be combined with natural biomaterials to create hybrid scaffolds that balance mechanical strength with biological responsiveness, particularly in alveolar bone regeneration.

Tissue engineering depends on the interaction among scaffolds, cells, and signaling molecules. Stem cells from dental pulp, periodontal ligament, bone marrow, and adipose tissue have shown potential for regeneration of bone, periodontal tissues, and soft tissue defects. Engineered biomaterials may recruit host cells and guide in situ regeneration, which is clinically relevant for ridge augmentation, peri-implant reconstruction, sinus augmentation, and maxillofacial rehabilitation.[6] Organoid systems and artificial intelligence may further support personalized regenerative strategies by predicting tissue response and optimizing scaffold design.[15,16]

Thus, biomimetic materials have expanded the biological foundation of prosthodontics by supporting cell function, angiogenesis, osteogenesis, and tissue integration. However, long-term clinical evidence, standardized protocols, and careful case selection remain necessary for their predictable routine use.

Table 1. Biomimetic Materials and Their Prosthodontic Applications

Biomimetic material	Relevant biological property	Prosthodontic application
Collagen	Extracellular matrix mimicry, biocompatibility, supports cell adhesion	Guided bone regeneration, guided tissue regeneration, soft tissue augmentation
Chitosan	Biodegradable, antimicrobial, supports wound healing	Scaffold fabrication, periodontal regeneration, implant surface modification
Hyaluronic acid	Promotes cell migration, angiogenesis, and wound healing	Ridge preservation, peri-implant soft tissue healing, regenerative procedures
Alginate hydrogel	Hydrophilic scaffold, cell encapsulation, controlled delivery	Drug delivery, tissue engineering, scaffold-based regeneration
Silk fibroin	High mechanical strength, slow degradation, biocompatibility	Bone regeneration, maxillofacial reconstruction, load-bearing scaffolds
Polycaprola ctone	Controlled degradation and structural stability	Three-dimensional scaffolds, alveolar bone regeneration, tissue-engineered constructs
Polyhydroxy alkanoates	Biocompatible biodegradable polymers	Bone tissue engineering and regenerative scaffold systems

Biological Tooth Replacement: Autotransplantation and Homotransplantation Biological tooth replacement is one of the most direct expressions of biomimetic prosthodontics. Unlike conventional fixed prostheses or osseointegrated implants, a transplanted tooth may preserve living periodontal ligament cells, proprioception, physiological mobility, and alveolar bone stimulation. Therefore, tooth transplantation attempts to restore the natural functional unit of tooth, periodontal ligament, and bone rather than replacing the missing tooth with an inert substitute.[5,8]

Autotransplantation refers to the transfer of a tooth from one site to another within the same individual. Its success depends largely on suitable donor tooth selection, atraumatic handling, and preservation of viable periodontal ligament cells. Teeth with incomplete root formation generally show better healing potential because pulpal revascularization and continued root development are more likely. Andreasen et al. reported favorable long-term outcomes in autotransplanted premolars when case selection and periodontal ligament preservation were carefully maintained.[8] In young patients, particularly after traumatic anterior tooth loss, autotransplantation may be valuable because implant placement is often delayed until skeletal growth is complete.[17]

Homotransplantation involves the transfer of a tooth from one individual to another. Its clinical use is limited because of concerns related to immune response, infection, ankylosis, and long-term survival. However, it remains scientifically relevant as an attempt to use a biological tooth as a natural prosthesis. Yang and Chang reported a tooth-bank homotransplantation case with continued root development and periodontal support after follow-up.[5] Advances in cryopreservation, immunological profiling, and tooth banking may improve its future applicability in selected cases. Healing after transplantation depends mainly on the periodontal ligament. If viable periodontal ligament cells remain, normal periodontal healing may occur. However, damage to these cells may lead to inflammatory resorption, replacement resorption, or ankylosis. Natiella et al. emphasized the importance of the periodontal membrane in determining healing after reimplantation.[18] Compared with implants, transplanted teeth offer proprioception, physiological mobility, orthodontic adaptability, and alveolar bone maintenance. However, they require suitable donor teeth, surgical precision, and interdisciplinary planning.[19,20]

Thus, autotransplantation and homotransplantation should be considered case-specific biological alternatives rather than routine substitutes for implants. Their greatest contribution lies in demonstrating the biomimetic ideal of replacing a missing tooth with a living functional unit capable of interacting with the surrounding tissues.

Table 2. Comparison of Dental Implants, Autotransplantation, and Homotransplantation

Parameter	Dental implant	Autotransplantation	Homotransplantation
Biological nature	Artificial replacement	Living biological replacement	Donor biological replacement
Periodontal ligament	Absent	Present if viable	Present if viable
Proprioception	Absent	Present	May be present
Physiological mobility	Absent	Present	May be present
Alveolar bone remodeling	Limited to osseointegration-related response	Physiological stimulation through PDL	Possible if periodontal healing occurs
Orthodontic movement	Not possible	Possible	Possible if periodontal healing is maintained
Root development	Not applicable	Possible in immature donor teeth	Possible in selected immature donor teeth
Technique sensitivity	Moderate	High	Very high
Major limitation	Lacks periodontal ligament and proprioception	Requires suitable donor tooth and precise technique	Immunological and storage-related concerns
Clinical relevance	Predictable option in adults	Valuable in young patients and selected cases	Limited use; potential future role with tooth banking

Clinical Applications in Prosthodontics

Biomimetics has wide clinical relevance in prosthodontics because it shifts treatment from mechanical replacement toward biological compatibility. In adhesive restorative dentistry, biomimetic principles emphasize preservation of sound tooth structure through bonded restorations, ceramic restorations, fiber-reinforced materials, veneers, endocrowns, and minimally invasive onlays. These approaches aim to reinforce the remaining tooth structure and distribute functional stresses more favorably.[1,2]

In fixed prosthodontics, biomimetics contributes to restoration design by reproducing natural morphology, emergence profile, proximal contacts, occlusal anatomy, and esthetic integration. CAD/CAM systems, when combined with virtual articulation and functional analysis, allow restorations to be designed according to individual tooth form and occlusal relationships rather than standardized templates.[3,9] This is particularly important in full-mouth rehabilitation, where minor occlusal discrepancies may contribute to prosthetic failure or patient discomfort.

In implant prosthodontics, biomimetic strategies aim to improve implant positioning, prosthetic emergence profile, occlusal design, osseointegration, and peri-implant tissue stability. Bioactive coatings, surface modifications, collagen membranes, hydrogels, and regenerative scaffolds may enhance tissue integration and improve esthetic outcomes.[4,6] Biomimetic scaffolds also support socket preservation, ridge augmentation, sinus augmentation, and localized defect reconstruction by encouraging cellular migration, vascular ingrowth, and new bone formation.[4,7]

Soft tissue reconstruction benefits from collagen matrices, hyaluronic acid-based materials, and bioactive scaffolds that improve peri-implant mucosal stability and esthetics.[4,6] In removable prosthodontics, biomimetic thinking is reflected in respecting residual ridge anatomy, mucosal resilience, neuromuscular control, and occlusal balance. In maxillofacial prosthodontics, computational design, three-dimensional printing, and bioinspired structures allow fabrication of lightweight, retentive, and patient-specific prostheses.[10] Biological tooth replacement through autotransplantation and homotransplantation further represents the ideal biomimetic goal of restoring a missing tooth with a living functional unit.[5,8,20]

Overall, biomimetics influences tooth preparation, material selection, prosthesis design, tissue regeneration, implant planning, and complex rehabilitation. Its greatest clinical contribution is the shift from replacing missing structures to restoring biological function, tissue harmony, and long-term adaptability.

Table 3. Emerging Technologies and Future Applications in Biomimetic Prosthodontics

Emerging technology	Potential prosthodontic application
Artificial intelligence	Restoration design, occlusal analysis, implant planning, prediction of tissue response
Three-dimensional bioprinting	Patient-specific scaffolds, bone regeneration, maxillofacial reconstruction
Smart biomaterials	Controlled release of bioactive molecules and improved tissue healing

Stem-cell-based therapy	Regeneration of bone, periodontal tissues, and soft tissue defects
Tooth banking and cryopreservation	Future support for autotransplantation and homotransplantation
Bioinspired CAD/CAM design	Customized restorations with improved morphology and stress distribution

Challenges and Limitations

Despite its promising role, biomimetics faces several limitations. Advanced biomaterials, digital workflows, regenerative scaffolds, and artificial intelligence-based systems are often expensive and may not be accessible in routine practice. Many biomimetic procedures are also technique-sensitive and require precise bonding protocols, careful surgical handling, and interdisciplinary planning.

Another limitation is the lack of sufficient long-term clinical evidence for many newer materials and regenerative approaches. Although laboratory and short-term studies are encouraging, their durability under functional oral conditions requires further validation. Moreover, complex tissues such as enamel, dentin, periodontal ligament, bone, and mucosa cannot yet be completely reproduced by artificial materials. Regulatory and ethical concerns also exist in stem cell therapy, tissue engineering, tooth banking, and biologic transplantation. Therefore, biomimetic approaches should be considered biologically guided adjuncts to conventional prosthodontic principles rather than universal replacements.

Future Perspectives

The future of biomimetics in prosthodontics will likely be shaped by artificial intelligence, three-dimensional bioprinting, smart biomaterials, and personalized regenerative medicine. AI may improve diagnosis, restoration design, occlusal analysis, implant planning, and prediction of tissue response by analyzing patient-specific anatomical and biological data.[16]

Three-dimensional bioprinting may allow fabrication of customized scaffolds containing cells, growth factors, and biomaterials for ridge augmentation, peri-implant reconstruction, and maxillofacial rehabilitation. Smart biomaterials capable of responding to biological stimuli and releasing therapeutic agents may improve healing and reduce complications.[11] Stem-cell-based approaches, engineered scaffolds, and improved cryopreservation protocols may eventually support regeneration of dental and supporting tissues and increase the feasibility of autotransplantation and homotransplantation.[19]

Although many of these approaches are still under investigation, they indicate a future in which prosthodontic treatment may become more biologically integrated, patient-specific, and functionally adaptive.

CONCLUSION

Biomimetics represents a significant advancement in prosthodontics by shifting the focus from mechanical replacement toward biologically integrated rehabilitation. Computational biomimetics has enhanced restoration design, stress distribution, and functional harmony. Natural biomaterials and tissue-engineered scaffolds have expanded possibilities for ridge preservation, peri-implant regeneration, soft tissue reconstruction, and maxillofacial rehabilitation.

Biological tooth replacement through autotransplantation and homotransplantation further demonstrates the potential of biomimetics by preserving periodontal ligament function, proprioception, and physiological bone remodeling. Although biomimetic prosthodontics is still evolving, its integration with artificial intelligence, regenerative medicine, smart biomaterials, and three-dimensional biofabrication may redefine future oral rehabilitation. Overall, biomimetics provides a scientifically sound framework for prosthodontic treatment that is functional, esthetic, conservative, and biologically harmonious.

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