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REVIEW ARTICLE

BIOMECHANICAL OPTIMIZATION OF IMPLANT-SUPPORTED PROSTHETIC REHABILITATION: A THEMATIC REVIEW OF FINITE ELEMENT EVIDENCE

Artak Heboyan[1]

[1]PhD, Associate Professor, Department Prosthodontic, Yerevan State Medical University after M. Heratsi, Yerevan, Armenia

***Corresponding author:** Artak Heboyan Associate professor of the Department of Prosthodontics Yerevan State Medical University after M. Heratsi,Yerevan, Armenia e-mail: heboyan.artak@gmail.com

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Abstract

Background: Implant-supported prosthetic rehabilitation involves complex biomechanical interactions in which stress distribution is governed by implant design, restorative materials, prosthetic configuration, and the condition of supporting tissues. Direct clinical assessment of internal stress remains limited; therefore, finite element analysis (FEA) has become a key tool for investigating these relationships.

Objective: To synthesize current finite element evidence and evaluate how implant geometry, material properties, prosthetic design, and clinical scenarios influence biomechanical performance in implant-supported prostheses.

Methods: A focused narrative review of published three-dimensional FEA studies was conducted. Evidence was analyzed thematically, with emphasis on implant macrodesign, framework and superstructure materials, implant positioning, and prosthetic configurations across clinically relevant scenarios, including short implants in D4 bone, zygomatic implant rehabilitation, socket shield techniques, implant-assisted removable partial dentures, and mandibular full-arch prostheses. Primary outcomes included von Mises stress, strain, displacement, and micromovement.

Results: Across the reviewed studies, implant macrodesign significantly influenced peri-implant biomechanics, particularly in compromised bone. Wider platform-switched short implants and square thread geometries consistently reduced stress, strain, and micromovement. Framework material stiffness also played a critical role: rigid materials such as zirconia, cobalt–chromium, and titanium decreased stress within implants and prosthetic components, whereas more flexible materials increased load transfer to these structures. In full-arch models, graphene frameworks demonstrated lower peri-implant stress compared with titanium. Implant positioning in distal-extension removable partial dentures showed comparable biomechanical behavior between premolar and molar sites. In socket shield models, increasing root fragment thickness led to progressive increases in stress and strain in both the retained root and surrounding bone.

Conclusions: Biomechanical performance in implant-supported prosthetic rehabilitation is governed by the combined interaction of implant geometry, material stiffness, prosthetic design, and anatomical context rather than by any single factor. Finite element analysis provides valuable comparative insight into stress distribution patterns and supports more informed, biomechanics-driven treatment planning in implant prosthodontics.

Keywords: FEA, dental implant, socket shield, implant design, prosthetic rehabilitation

INTRODUCTION

Implant-supported prosthetic rehabilitation has become a central treatment modality for the management of partial and complete edentulism, offering functional stability, improved load distribution, and enhanced patient satisfaction when compared with conventional removable or tissue-supported approaches. Nevertheless, the long-term success of these rehabilitations depends on a complex interaction between implant design, prosthetic configuration, framework material, bone quality, and loading conditions. Because these factors influence stress transfer to the peri-implant bone and prosthetic components, understanding their biomechanical behavior is essential for achieving predictable clinical outcomes [1-7]. In clinical practice, biomechanical challenges arise in a variety of prosthodontic scenarios. These include rehabilitation of severely resorbed ridges with short implants, management of atrophic maxillae with zygomatic implants, full-arch restorations supported by reduced numbers of implants, implant-assisted distal extension removable partial dentures, and immediate implant placement in esthetically demanding areas. Each of these situations presents a different mechanical environment, yet all share the same fundamental requirement: forces generated during function must be transferred in a way that minimizes harmful stress concentrations in bone, implants, abutments, screws, retained root fragments, and prosthetic frameworks [3,4,7].

Among the variables that may alter this biomechanical response, implant macrodesign has received considerable attention. Diameter, thread configuration, length, and platform switching are all believed to influence stress, strain, and micromovement at the bone-implant interface, especially in compromised bone. This is particularly relevant in D4 bone, where reduced density may compromise implant stability and increase the risk of unfavorable load transfer. Finite element findings from the included studies indicate that wider platform-switched short implants and favorable thread geometries may reduce peri-implant stress and improve biomechanical behavior under immediate loading conditions [1,8].

Material selection is another critical determinant of prosthetic performance. Framework and superstructure materials do not simply serve a restorative function; they actively influence the way occlusal loads are distributed throughout the implant-prosthesis-bone complex. In full-arch and zygomatic implant reconstructions, variations in material stiffness may alter stress concentration within implants, prosthetic screws, and surrounding bone. The included studies show that both conventional materials, such as titanium, cobalt-chromium, and zirconia, and newer alternatives such as graphene-based frameworks, may affect load transfer differently depending on the restorative design and clinical indication [3,5,6].

In addition to implant and material factors, prosthetic design itself remains a major source of biomechanical variation. For example, reducing the number of implants in a full-arch restoration may increase stress around distal implants and framework components, while implant position in implant-assisted removable partial dentures may alter leverage, displacement, and stress transmission to supporting structures. Likewise, in immediate implant placement with the socket shield technique, the thickness of the retained root fragment may influence stress distribution within both the fragment and adjacent bone. These observations emphasize that prosthetic rehabilitation should not be evaluated only from a surgical or restorative perspective, but rather as an integrated biomechanical system [2,4,7].

Because direct clinical measurement of internal stress and strain is difficult, finite element analysis has become one of the most widely used computational tools for investigating the biomechanics of implant dentistry. FEA allows complex anatomical structures and prosthetic assemblies to be modeled under controlled loading conditions, making it possible to compare alternative implant configurations, framework materials, and restorative designs. Across the selected papers, FEA was used to study short implants in poor-quality bone, residual root structures in socket shield procedures, zygomatic implant-supported superstructures, implant-assisted removable partial dentures, and full-arch mandibular prostheses supported by three or six implants. Collectively, these studies demonstrate the versatility of finite element modelling as a method for identifying stress concentration areas and exploring biomechanically favorable treatment designs [2-4,7].

At the same time, the value of finite element evidence lies not only in comparing isolated variables, but also in revealing broader trends relevant to clinical prosthodontics. Across these five studies, recurring themes include the importance of controlling peri-implant stress, selecting framework materials with appropriate stiffness, optimizing implant configuration in anatomically compromised situations, and recognizing that seemingly minor design modifications may produce meaningful biomechanical differences. These findings support the view that treatment planning in implant prosthodontics should be guided not only by anatomy and prosthetic feasibility, but also by biomechanical predictability[9,10].

Therefore, the purpose of this review is to synthesize the findings of these finite element studies and to critically examine how implant design, framework material, prosthetic configuration, and clinical scenario influence biomechanical behavior in implant-supported prosthetic rehabilitation. By integrating evidence from these selected papers, this review aims to provide a focused understanding of how computational biomechanical analysis can inform prosthodontic decision-making and support the optimization of restorative treatment strategies.

METHODOLOGY

his paper was prepared as a focused narrative review of selected finite element (FE) investigations addressing the biomechanics of implant-supported prosthetic rehabilitation. The literature search was conducted using electronic databases, including PubMed, Scopus, and Web of Science. The search focused on studies published in recent years that investigated the biomechanics of implant-supported prosthetic systems using finite element analysis (FEA).

This review was designed to provide a critical and clinically oriented synthesis rather than a systematic review or meta-analysis. Its primary aim was to integrate evidence on how implant design, prosthetic configuration, framework materials, and clinical treatment scenarios influence stress distribution and related biomechanical behavior in implant dentistry.

Studies were included if they employed three-dimensional finite element analysis to evaluate stress distribution in implant-supported prosthetic systems and reported quantitative biomechanical outcomes such as von Mises stress, strain, displacement, or micromovement. Studies that were not directly related to prosthetic biomechanics or lacked quantitative biomechanical outcomes were excluded.

The literature considered in this review was limited to previously published in silico studies directly relevant to implant-supported prosthetic biomechanics. The selected studies represented a range of clinically relevant scenarios, including short implants in poor-quality bone, socket shield techniques in immediate implant placement, zygomatic implant-supported rehabilitations, implant-assisted distal extension removable partial dentures, and mandibular full-arch prostheses with varying implant configurations and framework materials. This approach ensured that the review remained focused on prosthodontically relevant applications of finite element analysis while capturing variability in biomechanical design and clinical context.

All included studies were analyzed in full text and synthesized using a thematic approach. Rather than presenting findings chronologically, the studies were grouped according to major biomechanical themes, including implant macrodesign and peri-implant biomechanics, the effects of framework and superstructure materials, implant positioning and prosthetic configuration, and biomechanical behavior in specific clinical situations. This structure enabled comparison of related findings across different models and facilitated the identification of broader biomechanical patterns relevant to prosthodontic treatment planning.

For each study, the analysis focused on key methodological and outcome-related variables, including simulation objectives, digital model characteristics, software platforms, assumptions regarding material properties, implant and prosthetic design variables, loading conditions, and primary biomechanical outcomes. Particular attention was given to commonly used FEA outputs such as von Mises stress, strain, displacement, and micromovement, as these parameters formed the basis for comparison across studies.

Figure 1 illustrates the principal biomechanical outcome parameters reported in the included FEA studies. These parameters represent the main indicators used to evaluate stress distribution and mechanical behavior in finite element models.

Parameter	Definition	Clinical Relevance
von Mises Stress	Equivalent stress in materials	Predicts risk of mechanical failure
Strain	Deformation of bone	Indicates risk of bone remodeling/resorption
Displacement	Movement under load	Reflects prosthetic stability
Micromovement	Small implant motion	Critical for osseointegration success

Figure 1 Biomechanical Outcome Parameters in FEA Studies

The included studies shared methodological similarities, such as three-dimensional modeling, defined boundary conditions, and controlled loading protocols. However, they differed in terms of geometric modeling, material assumptions, force application, and the specific structures analyzed.

Due to this heterogeneity, the synthesis was descriptive and interpretive rather than quantitative. Statistical pooling was not performed because of substantial variability in simulated anatomy, implant dimensions, prosthetic designs, material properties, and loading conditions. Instead, emphasis was placed on identifying recurring biomechanical trends, clinically relevant differences, and areas of agreement across the literature.

In addition to summarizing findings, this review included a critical appraisal of the inherent limitations of finite element analysis. Common modeling assumptions—such as isotropic and homogeneous material behavior, idealized bone–implant contact, simplified loading conditions, and limited representation of biological adaptation—were considered when interpreting the results. This ensured that the conclusions remained methodologically balanced and clinically applicable.

As a narrative review, this study did not follow a formal systematic review protocol and may therefore be subject to selection bias. However, efforts were made to include representative studies covering a broad spectrum of clinically relevant biomechanical scenarios.

Overall, the methodology was intended to provide a structured synthesis of finite element evidence relevant to implant-supported prosthetic rehabilitation. By organizing the literature around shared biomechanical themes, the review clarifies how computational modeling contributes to understanding treatment design, material selection, and stress distribution in prosthodontic practice.

RESULTS

The reviewed finite element studies consistently demonstrated that biomechanical behavior in implant-supported prosthetic rehabilitation is strongly influenced by the interaction between implant design, framework or superstructure materials, prosthetic configuration, and the specific clinical scenario being simulated. Across the included papers, the principal outcomes assessed were von Mises stress, strain, displacement, and micromovement, which were used to compare alternative treatment designs under controlled loading conditions. Despite differences in model construction and clinical application, several recurring biomechanical patterns were identified.

One major finding was that implant macrodesign significantly affects peri-implant biomechanics, particularly under compromised bone conditions.

Figure 2 summarizes the relationship between implant design variables and their biomechanical effects.

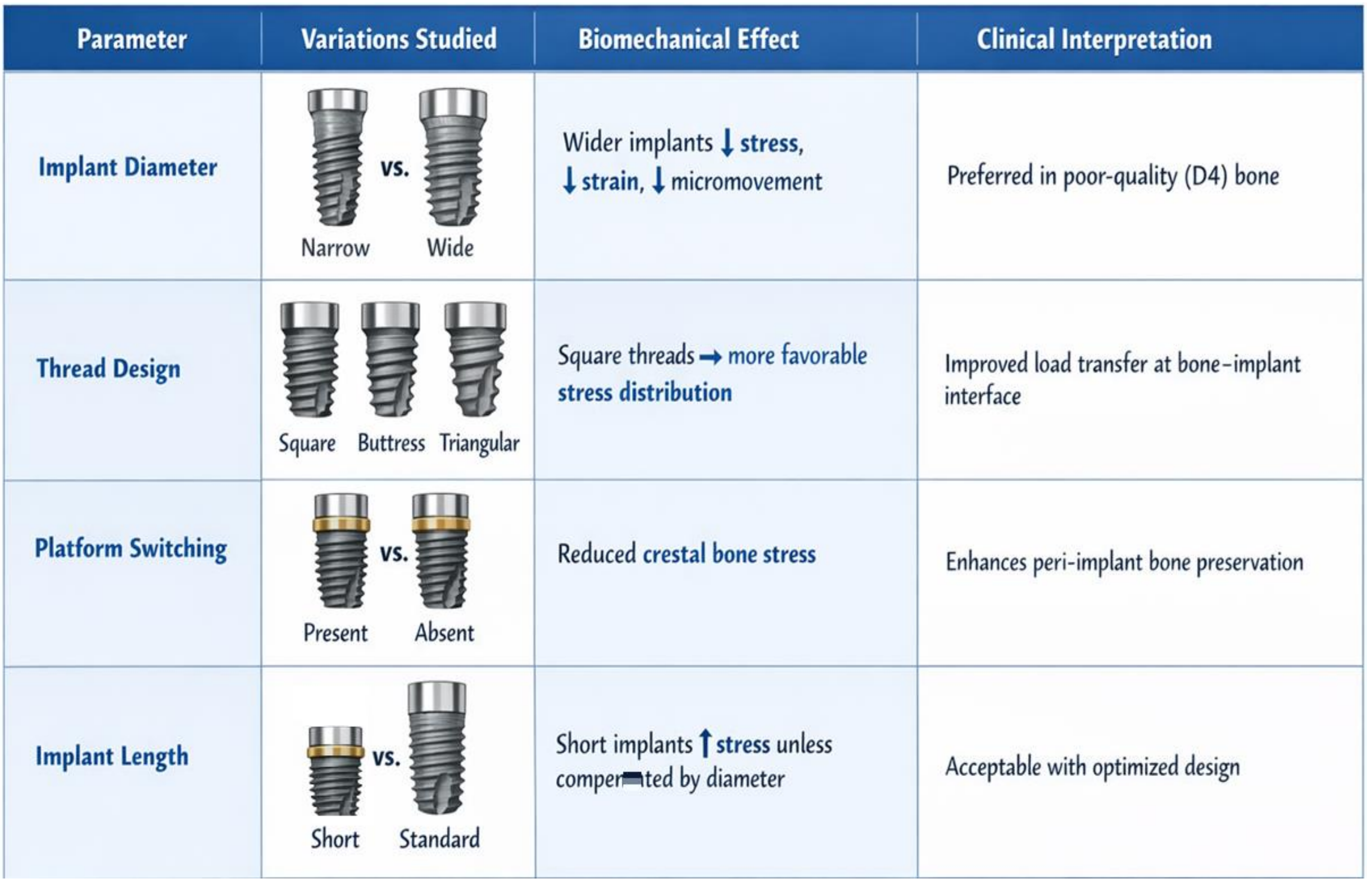

Figure 2. Comparison of Implant Design Variables and Biomechanical Outcomes

In the study of short implants placed in D4 bone, increasing implant diameter was associated with reduced peri-implant von Mises stress, reduced strain, and reduced micromovement under both axial and oblique loading conditions. Among the tested designs, the 6 mm diameter platform-switched short implant demonstrated the most favorable biomechanical performance, with peri-implant von Mises stress values of 3.3 MPa (axial loading) and 35.1 MPa (non-axial loading), strain values of 194 Ɛ and 484 Ɛ, and micromovement values of 0.7 µm and 1.3 µm, respectively. In the same study, square microthreads showed superior performance compared with buttress and triangular thread designs, producing more favorable stress distribution in the surrounding bone tissue [1].

A second major pattern was the significant influence of framework and superstructure material stiffness on stress transfer within implant-supported restorations.

The mechanical behavior of commonly used framework materials is summarized in Table 1.

Table 1. Framework / Superstructure Materials and Stress Distribution

Material	**Elastic Modulus**	**Observed Behavior**	**Biomechanical Outcome**
Titanium	High	Standard reference material	Moderate stress distribution
Cobalt–Chromium	Very high	High rigidity	Reduced stress in implants/screws
Zirconia	High	Stiff ceramic	Favorable stress reduction
PEEK	Low	Flexible behavior	Higher stress in implants
Carbon fiber polymer	Moderate	Semi-rigid response	Intermediate performance
Graphene	Variable (advanced)	High strength with flexibility	Reduced peri-implant stress (experimental evidence)

In the zygomatic implant model, all tested superstructure materials produced a relatively homogeneous strain distribution in the supporting bone, indicating that each material could potentially be used for reconstruction of the edentulous maxilla. However, stiffer materials such as zirconia, cobalt–chromium, and titanium were more effective in reducing stresses in the zygomatic implants and prosthetic screws compared with more flexible materials such as carbon fiber polymer and PEEK. This suggests that although multiple materials may be biomechanically acceptable, those with a higher elastic modulus may be more advantageous when the clinical objective is to minimize stress concentration in implants and fixation components [3,6].

A similar material-dependent trend was observed in mandibular full-arch models comparing titanium and graphene frameworks. In all simulated conditions, the highest stresses were consistently concentrated at the neck of the most distal implant. However, graphene frameworks generally resulted in lower peri-implant stress compared with titanium frameworks. In the conventional six-implant model, cortical bone stress in the implant region was 25.27 MPa for titanium and 12.18 MPa for graphene. In the three-implant tilted model under vertical loading, cortical stress values were 70.31 MPa for titanium and 21.27 MPa for graphene. These findings indicate that framework material significantly influences load transfer to the supporting bone, with graphene demonstrating more favorable stress distribution in the tested full-arch mandibular configurations [5].

The reviewed studies also indicated that prosthetic configuration and implant position may influence biomechanical response, although not always in a statistically significant manner. In the implant-assisted distal extension removable partial denture model, no statistically significant differences were observed between premolar and molar implant placement in terms of von Mises stress or displacement. Although the premolar group demonstrated slightly higher values, the differences were not statistically significant, suggesting that both implant positions are biomechanically acceptable under the tested loading conditions. At 125 N, framework stress values were 28.71 ± 1.10 MPa for the premolar group and 25.56 ± 4.89 MPa for the molar group, indicating comparable mechanical performance [4].

In contrast, the socket shield model demonstrated that relatively small geometric changes in retained root fragments may produce progressive increases in stress and strain. As root fragment thickness increased from 0.5 mm to 2.0 mm during immediate implant placement, both stress and principal strain increased in the residual root and surrounding bone. Maximum stress in the root fragment increased from 12.68 MPa at 0.5 mm thickness to 28.74 MPa at 2.0 mm thickness, while bone stress increased from 5.61 MPa to 11.38 MPa over the same range. Principal strain values followed a similar increasing trend.

Although shield thicknesses between 0.5 mm and 2.0 mm did not produce catastrophic stress conditions in any model, the results indicated that increasing shield thickness is associated with progressively higher biomechanical loading. Based on these findings, a thickness of approximately 1.5 mm may represent a more favorable upper limit from a biomechanical standpoint [2].

A comparison of clinical scenarios and their biomechanical implications is presented in Table 2.

Table 2. Prosthetic Configuration & Clinical Scenario Analysis

Clinical Scenario	Variable Studied	Key Finding	Clinical Implication
Short implants (D4 bone)	Diameter, thread design	Wider implants and square threads most favorable	Macrodesign can compensate for poor bone quality
Zygomatic implants	Material stiffness	Stiffer materials reduce stress	Prefer rigid frameworks when possible
Full-arch prosthesis	Framework material	Graphene reduces stress vs titanium	Promising but still experimental
Implant-assisted RPD	Implant position	Premolar ≈ molar	Flexible implant placement possible
Socket shield	Root fragment thickness	Increased thickness → increased stress	Limit thickness (~1.5 mm)

A visual comparison of stress distribution across different clinical scenarios is presented in Figure 3.

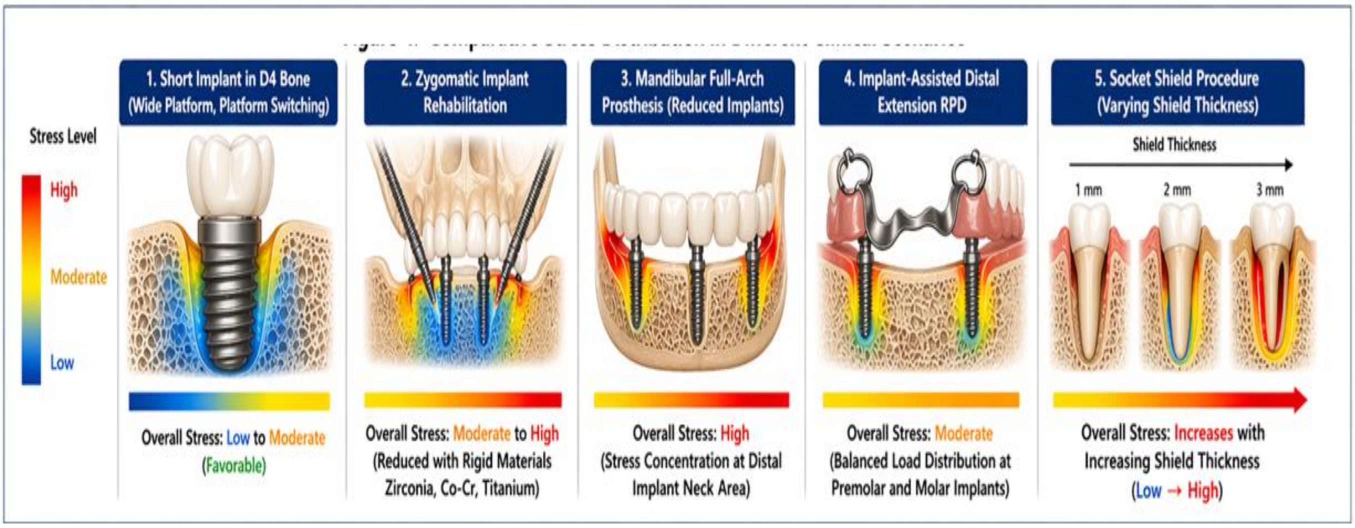

Figure 3. Comparative stress distribution patterns across implant-supported prosthetic scenarios

Comparative stress patterns in five clinical scenarios simulated by finite element analysis are illustrated. Color maps indicate von Mises stress distribution in bone and peri-implant regions. Stress levels vary according to implant design, prosthetic configuration, and clinical condition.

When considered collectively, the reviewed evidence indicates that favorable biomechanical performance is generally associated with designs that reduce stress concentration at critical interfaces, particularly in peri-implant bone, implant neck regions, and prosthetic connection areas. Wider short implants with square thread designs, stiffer superstructure materials in zygomatic reconstructions, graphene frameworks in full-arch mandibular models, and clinically adaptable implant positions in distal-extension removable prostheses all demonstrated biomechanical advantages within their respective simulation conditions. At the same time, the results highlight that the effect of any single variable cannot be interpreted in isolation, as overall stress distribution depends on the complex interaction between implant geometry, restorative design, material properties, and anatomical conditions [3–5,7].

Overall, the findings support the usefulness of finite element analysis as a comparative tool for evaluating biomechanically favorable treatment options in implant prosthodontics. The evidence consistently demonstrates that computational modeling can detect meaningful differences between alternative implant designs, materials, and prosthetic configurations, thereby contributing to a more informed biomechanical interpretation of treatment planning decisions.

DISCUSSION

The findings of this review suggest that finite element analysis offers a valuable framework for interpreting how biomechanical behavior in implant-supported prosthetic rehabilitation is shaped by multiple interacting variables. Although each study focused on a specific clinical scenario, a consistent pattern emerged: successful outcomes depend not only on achieving osseointegration but also on effectively controlling stress distribution within the implant–prosthesis–bone complex [11–13]. At the same time, these observations should be interpreted with caution, as they are based on computational models that inevitably simplify biological reality.

One of the most consistent observations across the reviewed evidence is the importance of minimizing peri-implant stress in compromised anatomical conditions. In the short implant model in D4 bone, wider platform-switched implants with square threads showed the most favorable distribution of stress, strain, and micromovement, suggesting that macrodesign modifications may partially compensate for poor bone quality. This is clinically significant because it supports the rationale for using short, wide-diameter implants in anatomically restricted sites where vertical bone height is limited and more invasive augmentation procedures may be undesirable. These findings imply that implant design should be regarded not merely as a structural feature but as a biomechanical strategy for improving force transmission in weak supporting bone [1,14].

The review also highlights the strong influence of restorative material properties on stress transfer. Both the zygomatic implant study and the full-arch mandibular framework study demonstrated that material stiffness substantially alters biomechanical response. In zygomatic rehabilitation, stiffer superstructure materials such as zirconia, cobalt–chromium, and titanium reduced stress in implants and prosthetic screws more effectively than more flexible materials. By contrast, in mandibular full-arch models, graphene frameworks showed lower peri-implant stress than titanium under the simulated loading conditions. These findings suggest that the "optimal" material cannot be defined universally but depends on the specific biomechanical objective. A stiffer material may reduce mechanical demand in prosthetic screws and implants, whereas alternative materials may improve load dissipation to surrounding structures in different configurations. Therefore, framework selection should be prosthetically and anatomically contextual rather than based solely on familiarity or conventional preference [3,15].

Another important point arising from the reviewed studies is that biomechanical optimization does not always require anatomically ideal treatment conditions. In the implant-assisted distal extension removable partial denture model, premolar and molar implant positions showed no statistically significant differences in stress distribution or displacement. This finding has practical relevance because distal-extension cases are often constrained by ridge resorption, mental foramen position, or limited posterior bone availability. From a clinical perspective, the results suggest that when distal placement is not feasible, a mesially positioned implant may still provide an acceptable biomechanical alternative. This shifts the focus from achieving a theoretically ideal position to selecting a clinically feasible and biomechanically adequate solution [4,16].

The socket shield study further reinforces the concept that even relatively small design or dimensional changes may alter the biomechanical environment. As the thickness of the retained root fragment increased, both stress and principal strain in the root structure and surrounding bone increased progressively. This suggests that preservation-oriented procedures, although attractive from an esthetic and tissue-maintenance perspective, must also be evaluated from a biomechanical standpoint. In other words, biologically conservative treatment concepts do not automatically ensure mechanically favorable conditions. The conclusion that a thickness of approximately 1.5 mm may represent a safer upper practical threshold reflects the broader principle that prosthodontic and implant planning should balance tissue preservation with mechanical stability [2,17].

Taken together, these results support the view that implant-supported prosthetic rehabilitation should be interpreted as an integrated system rather than a collection of isolated components. Changes in one variable—such as implant diameter, thread design, superstructure stiffness, or implant position—may reduce stress in one region while redistributing it elsewhere. This systems-based perspective is particularly important in full-arch reconstructions and complex implant scenarios, where small changes in geometry or material behavior may have amplified effects across the restoration [1,5]. The reviewed evidence therefore argues against simplistic conclusions and instead supports a more comprehensive biomechanical approach to treatment planning.

At the same time, the discussion of these findings must acknowledge the methodological limitations inherent to finite element analysis. Across the reviewed studies, simulations relied on assumptions such as homogeneous or isotropic material behavior, idealized bone–implant contact, simplified loading conditions, and limited representation of biological adaptation over time. Even when anisotropic properties or convergence testing were incorporated, the models remained simplifications of highly complex clinical conditions. Consequently, the findings should not be interpreted as direct clinical predictions but rather as comparative biomechanical indicators that help identify trends, risk zones, and potentially favorable treatment strategies.

Despite these limitations, the translational value of finite element evidence remains substantial. The reviewed studies demonstrate that computational modeling can guide hypothesis generation, refine prosthetic design choices, and support clinical decision-making in scenarios where direct measurement of internal stress is not feasible. This is particularly valuable in prosthodontics, where clinicians often choose among several technically viable options that differ in their long-term mechanical implications. Finite element analysis does not replace clinical evidence but enhances preclinical reasoning by clarifying how different configurations may behave before clinical application.

Overall, the reviewed evidence suggests that biomechanically favorable implant rehabilitation is more likely to be achieved when treatment planning incorporates design-based stress control from the outset. Wider short implants with favorable thread geometry, careful material selection for superstructures and frameworks, context-sensitive implant placement, and awareness of the mechanical implications of tissue-preservation techniques all contribute to more balanced stress distribution. Thus, the primary contribution of these studies lies not only in comparing isolated designs but also in demonstrating that computational biomechanics can serve as a critical bridge between restorative planning and mechanical predictability in implant prosthodontics.

To summarize the integrated biomechanical effects across all reviewed scenarios, Table 3 presents a consolidated synthesis of key variables and their clinical implications.

Table 3. Integrated biomechanical response of implant-supported prosthetic systems

Factor	**Modification**	**Biomechanical Effect**	**Clinical Interpretation**
Implant diameter	Increase	↓ Stress, ↓ micromovement	Preferred in poor bone quality
Thread design	Square vs triangular	Square = more favorable stress distribution	Improves load transfer
Platform switching	Present	↓ Crestal bone stress	Reduces marginal overload
Framework stiffness	High (Ti, Co-Cr, Zr)	↓ Implant/screw stress	More favorable for rigid load transfer
Flexible frameworks	PEEK, polymer	↑ Implant stress	More stress absorption in prosthesis
Graphene framework	Advanced composite	↓ Bone stress (experimental)	Promising but not clinical standard
Implant position	Premolar vs molar	Similar biomechanical outcome	Flexible placement possible
Socket shield thickness	Increase	↑ Stress & strain	Limit ~1.5 mm recommended

Figure 4 illustrates the key factors influencing biomechanical behavior in implant-supported prosthetic rehabilitation. Implant geometry, bone quality, framework material, and loading direction interact to determine stress transfer pathways. These interactions affect peri-implant bone, implant components, framework, micromotion, and strain distribution, which ultimately influence long-term clinical success.

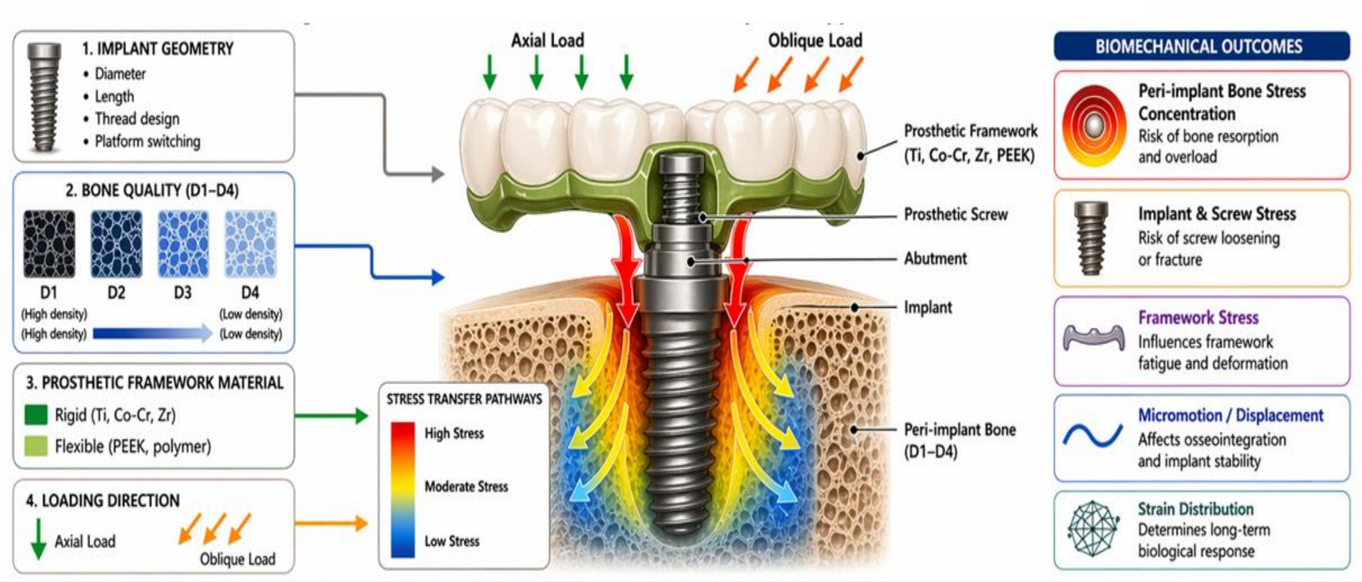

Figure 4. Biomechanical interaction model of implant-supported prosthetic rehabilitation

Limitations

Despite the valuable insights provided by this review, several limitations must be acknowledged. First, the included studies are based exclusively on finite element analysis (FEA), which inherently relies on mathematical modeling and computational assumptions rather than direct clinical or in vivo measurements. As a result, all findings should be interpreted within the context of theoretical simulations rather than real biological conditions.

A major limitation common to all included FEA studies is the simplification of complex biological systems. Most models assume homogeneous, isotropic, and linearly elastic material properties for bone, implants, and prosthetic components, whereas, in reality, bone is anisotropic, heterogeneous, and exhibits time-dependent behavior. These simplifications may influence the absolute values of stress and strain reported in the studies, even if relative comparisons between models remain valid.

In addition, the majority of simulations used idealized bone–implant contact conditions, typically assuming complete osseointegration with perfect bonding between the implant and bone. This does not fully reflect clinical reality, where microgaps, partial osseointegration, or variations in bone quality may significantly alter stress distribution and micromovement.

Another limitation is the use of static loading conditions in most models. Functional mastication is a dynamic process involving cyclic, multidirectional forces that vary in magnitude and direction over time. Static or simplified loading scenarios may therefore underestimate fatigue-related phenomena and the long-term biomechanical behavior of implant-supported restorations.

Furthermore, there was considerable heterogeneity among the included studies in terms of implant geometry, prosthetic design, loading magnitude, boundary conditions, and software platforms used for analysis. This variability limits direct comparability between studies and prevents quantitative synthesis of results. Although a thematic synthesis was performed, the lack of standardized modeling protocols remains a significant limitation in FEA-based literature.

It is also important to recognize that biological processes such as bone remodeling, adaptation, and resorption were not incorporated into the simulations. Consequently, the reviewed studies primarily reflect initial mechanical responses rather than long-term biological–mechanical interactions that occur in clinical settings.

Future Directions

Future research in finite element analysis of implant-supported prosthetic rehabilitation should aim to improve the biological realism and clinical applicability of computational models. One important direction is the development of more advanced material models that better represent the anisotropic, viscoelastic, and heterogeneous properties of bone and soft tissues. Incorporating patient-specific bone quality derived from imaging data, such as CT-based density mapping, could significantly enhance the accuracy of biomechanical predictions.

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Another important area for future investigation is the integration of dynamic and fatigue loading conditions into finite element simulations. Since implant-supported prostheses are subjected to repeated cyclic forces during mastication, future models should incorporate time-dependent loading to better simulate clinical function and to evaluate long-term failure risks such as screw loosening, implant fatigue, and marginal bone loss.

The incorporation of bone remodeling algorithms into FEA models also represents a critical future advancement. By simulating adaptive bone responses to mechanical loading over time, researchers could better understand how stress distribution influences long-term peri-implant bone stability and resorption patterns.

In addition, future studies should focus on standardizing finite element modeling protocols, including boundary conditions, material properties, and loading parameters. Such standardization would improve comparability between studies and facilitate the development of more robust evidence synthesis in biomechanical implant research.

Another promising direction is the use of patient-specific, three-dimensional models derived from real clinical cases. Personalized finite element models could allow clinicians to simulate different implant positions, prosthetic designs, and material combinations before treatment, thereby supporting individualized treatment planning and precision prosthodontics.

Finally, future research should explore the integration of finite element analysis with artificial intelligence and machine learning approaches. Such integration may enable the prediction of biomechanical outcomes across large datasets, allowing faster optimization of implant designs and prosthetic configurations based on clinical variables.

This review highlights the important role of finite element analysis in advancing the biomechanical understanding of implant-supported prosthetic rehabilitation. Across different prosthodontic scenarios, the evidence consistently shows that stress distribution is not determined by a single variable but by the combined influence of implant geometry, restorative material, prosthetic design, and anatomical context. The reviewed studies demonstrate that wider platform-switched short implants with favorable thread geometry may improve biomechanical behavior in poor-quality bone, that framework and superstructure stiffness substantially influence load transfer in full-arch and zygomatic rehabilitations, and that clinically constrained alternatives, such as premolar implant positioning in distal-extension removable prostheses, may still provide acceptable biomechanical performance.

At the same time, procedures aimed at preserving tissues, such as the socket shield technique, must also be evaluated from a mechanical perspective because increasing structural dimensions may alter stress patterns in both retained tissues and surrounding bone. Taken together, these findings indicate that finite element evidence is valuable not only for comparing specific treatment options but also for supporting a more integrated approach to implant prosthodontic planning.

Although computational models cannot fully reproduce the complexity of the biological environment, they remain highly useful for identifying stress concentration zones, clarifying biomechanical tendencies, and guiding the optimization of implant-supported restorative strategies. Therefore, finite element analysis should be regarded as an important adjunct in prosthodontic research and treatment planning, with particular relevance for improving mechanical predictability in complex implant rehabilitation.

Finite element evidence may assist clinicians in selecting implant designs, framework materials, and prosthetic configurations that promote more favorable stress distribution and improved mechanical predictability in complex implant rehabilitation. Nevertheless, further validation through clinical and long-term observational studies is necessary to confirm how closely these computational findings translate into real-world outcomes.

CONCLUSION

Biomechanical performance in implant-supported prosthetic rehabilitation is influenced by the interaction of implant geometry, material properties, prosthetic design, and anatomical conditions rather than by any single variable alone. Finite element analysis provides a useful comparative framework for understanding these relationships and for identifying treatment approaches that may reduce unfavorable stress concentration. While such models cannot fully replicate clinical reality, they offer valuable insight for improving preclinical planning and enhancing mechanical predictability in complex implant rehabilitation.

DECLARATIONS

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Competing Interests

The authors declare no conflict of interest.

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