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Digital Occlusion in Contemporary Prosthodontics: Current Evidence, Artificial Intelligence, and Future Perspectives

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Abstract

Accurate occlusal assessment is essential for successful prosthodontic rehabilitation, influencing masticatory efficiency, prosthesis longevity, patient comfort, and long-term treatment outcomes. Conventional methods, including articulating paper, shimstock foil, and wax records, remain widely used; however, these techniques are subjective and provide limited information regarding occlusal force distribution, contact timing, and dynamic mandibular function. Advances in digital dentistry have introduced computerized occlusal analysis systems, intraoral scanners, CAD/CAM technology, virtual articulators, jaw-motion analysis, and artificial intelligence (AI), enabling more objective, quantitative, and patient-centered approaches to occlusal assessment.

This evidence-based narrative review critically evaluates contemporary evidence on digital occlusion in prosthodontics, focusing on computerized occlusal analysis, digital workflows, CAD/CAM technology, virtual articulators, AI applications, clinical utility, current challenges, research gaps, and future perspectives. A structured literature search was conducted using PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar to identify relevant English-language publications published between January 2015 and June 2026, while landmark studies published before 2015 were included to provide historical context. Evidence from systematic reviews, meta-analyses, randomized controlled trials, clinical studies, observational studies, and clinically relevant narrative reviews was critically synthesized.

Current evidence suggests that computerized occlusal analysis provides objective and reproducible assessment of occlusal contacts, relative force distribution, contact timing, and dynamic occlusal relationships, overcoming many limitations of conventional qualitative techniques. Integration with digital workflows has improved prosthesis accuracy, communication, and treatment efficiency while reducing chairside occlusal adjustments. Although AI shows considerable potential for diagnosis, treatment planning, and prosthesis design, robust clinical validation remains limited. Overall, digital occlusal technologies represent valuable adjuncts to contemporary prosthodontic practice; however, standardized protocols, high-quality multicenter clinical studies, and stronger evidence are needed to

support their widespread implementation and facilitate the transition toward evidence-based precision prosthodontics.

Keywords: Prosthodontics; Digital occlusion; Computerized occlusal analysis; Digital dentistry; Digital workflow; CAD/CAM; Virtual articulator; Artificial intelligence.

1. Introduction

Occlusion is a fundamental determinant of functional and biological success in prosthodontic rehabilitation. The establishment and maintenance of harmonious occlusal relationships are essential for restoring masticatory efficiency, speech, esthetics, patient comfort, and the long-term stability of prosthetic restorations.[1] Inadequate occlusal management may contribute to biological and mechanical complications, including excessive tooth wear, prosthesis fracture, screw loosening, implant overload, temporomandibular disorders (TMDs), compromised prosthesis longevity, and reduced patient satisfaction.[2] Consequently, accurate occlusal assessment remains an indispensable component of prosthodontic diagnosis, treatment planning, prosthesis fabrication, insertion, and long-term maintenance.[3]

Traditionally, occlusal evaluation has relied on qualitative clinical methods such as articulating paper, shimstock foil, wax occlusal records, photo occlusion, occlusion spray ,transparent acetate sheet, polyether occlusion indicator, Alginate impression material , pressure-indicating materials, and clinical examination.[4-6,35] These techniques remain widely used because they are inexpensive, simple, and readily available. However, they provide only limited information regarding the magnitude, timing, sequence, and distribution of occlusal forces, while interpretation is largely dependent on clinician experience. This inherent subjectivity may reduce reproducibility and limit diagnostic precision, particularly in complex prosthodontic rehabilitations requiring highly accurate occlusal control.

Over the past two decades, digital dentistry has transformed prosthodontic practice by introducing technologies that enhance diagnostic accuracy, treatment planning, laboratory communication, and prosthesis fabrication. The widespread adoption of intraoral scanners (IOS), cone-beam computed tomography (CBCT), computer-aided design and computer-aided manufacturing (CAD/CAM), facial scanners, virtual articulators, and digital patient concepts has enabled comprehensive digital workflows that improve clinical efficiency while minimizing cumulative procedural errors.[6-9] These innovations have facilitated more precise prosthesis fabrication, reduced chairside adjustments, shortened treatment time, and improved patient experience.

One of the most significant developments within this digital transformation has been the introduction of computerized occlusal analysis. Unlike conventional qualitative indicators, computerized systems such as T-Scan and newer digital occlusal analysis technologies objectively record occlusal contact sequence, relative force distribution, occlusion and disclusion times, and dynamic mandibular movements in real time.[10] These quantitative data enable clinicians to identify premature contacts, occlusal interferences, and functional force imbalances that may be difficult to detect using traditional methods alone. Consequently, computerized occlusal analysis has become an important adjunct in fixed prosthodontics, implant-supported rehabilitation, complete dentures, full-mouth rehabilitation, occlusal splint therapy, and management of selected TMD patients.[11]

Simultaneously, advances in digital workflow integration have expanded occlusal assessment beyond isolated contact analysis. Virtual articulators, digital facebows, jaw-tracking systems, patient-specific mandibular motion analysis, and digital patient platforms now allow clinicians to simulate functional occlusion within a virtual environment before prosthesis fabrication.[12] The integration of these technologies facilitates individualized prosthesis design, improves interdisciplinary communication, and enhances the predictability of prosthodontic rehabilitation by incorporating both anatomical and functional patient-specific information.

More recently, artificial intelligence (AI) has emerged as a promising extension of digital prosthodontics. Machine learning and deep learning algorithms are increasingly being investigated for automated image interpretation, prosthesis design, treatment planning, prediction of occlusal discrepancies, and optimization of digital workflows.[13] Although current clinical applications remain limited, AI has the potential to integrate large volumes of patient-specific data, support evidence-based clinical decision-making, and enable more personalized prosthodontic care. As digital technologies continue to evolve, AI-assisted occlusal analysis may further improve diagnostic accuracy, treatment efficiency, and long-term clinical outcomes.[14]

Despite these technological advances, the available literature remains fragmented. Most published studies evaluate individual technologies—such as computerized occlusal analysis, CAD/CAM systems, virtual articulators, digital workflows, implant occlusion, or artificial intelligence—in isolation. Comprehensive reviews integrating these rapidly evolving technologies within the broader context of contemporary prosthodontic practice remain limited.[15] Furthermore, heterogeneity in study design, outcome measures, clinical protocols, and follow-up periods makes it challenging to translate existing evidence into standardized clinical recommendations. High-quality prospective studies evaluating integrated digital and AI-assisted occlusal workflows are also relatively scarce.

Given the rapid evolution of digital dentistry and the growing emphasis on precision prosthodontics, an updated evidence-based synthesis is both timely and clinically relevant. A comprehensive review integrating current evidence on computerized occlusal analysis, digital workflows, virtual articulators, CAD/CAM technology, and artificial intelligence may provide clinicians, researchers, and postgraduate students with a clearer understanding of contemporary concepts, clinical applications, existing limitations, research gaps, and future directions.

Therefore, the aim of this evidence-based narrative review is to critically evaluate the current evidence on digital occlusion in prosthodontics, with emphasis on computerized occlusal analysis, digital workflows, CAD/CAM technologies, virtual articulators, and emerging artificial intelligence applications. In addition, this review identifies existing challenges, research gaps, and future perspectives to support the evidence-based integration of digital occlusal technologies into contemporary prosthodontic practice.

2. Search Strategy and Review Methodology

This evidence-based narrative review was conducted through a structured and comprehensive literature search to identify contemporary evidence on digital occlusion and its applications in prosthodontics. The review methodology was designed to ensure broad coverage of relevant literature while maintaining scientific rigor in literature selection, critical appraisal, and evidence synthesis.

Electronic literature searches were performed in **PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar**. The primary search included articles published between **January 2015 and June 2026**, while seminal landmark publications published before 2015 were included where necessary to provide historical context regarding the evolution of occlusal concepts, prosthodontic philosophies, and computerized occlusal analysis.

The search strategy combined **Medical Subject Headings (MeSH)** and free-text keywords using Boolean operators (**AND**, **OR**). The principal search terms included *digital occlusion, computerized occlusal analysis, T-Scan, OccluSense, prosthodontics, digital dentistry, CAD/CAM, virtual articulator, digital workflow, intraoral scanner, digital patient, jaw-motion analysis, implant occlusion, artificial intelligence, machine learning,* and *deep* *learning*. Search strategies were adapted according to the indexing systems of each electronic database. Additionally, the reference lists of relevant review articles and landmark publications were manually screened to identify further eligible studies.

Eligible publications included systematic reviews, meta-analyses, randomized controlled trials, prospective and retrospective clinical studies, observational studies, pilot studies, consensus statements, position papers, and clinically relevant narrative reviews addressing digital occlusion or digital prosthodontics. Preference was given to higher levels of evidence whenever available while also incorporating landmark publications considered fundamental to the historical development of occlusal concepts and digital technologies.

Studies were excluded if they were unrelated to prosthodontics, focused exclusively on orthodontics or maxillofacial surgery without relevance to prosthodontic occlusion, were editorials, letters to the editor, conference abstracts lacking adequate methodological information, duplicate publications, or non-English articles.

Retrieved records were screened according to their titles and abstracts, followed by full-text assessment of potentially eligible publications. Studies meeting the predefined eligibility criteria were critically appraised and narratively synthesized under the following thematic areas:

- Evolution of occlusal concepts
- Conventional occlusal assessment
- Computerized occlusal analysis
- Digital prosthodontic workflows
- CAD/CAM technologies
- Virtual articulators and jaw-motion analysis
- Artificial intelligence
- Clinical applications
- Current challenges
- Research gaps
- Future perspectives

As this manuscript represents an **evidence-based narrative review**, formal risk-of-bias assessment and quantitative meta-analysis were not performed. Instead, the available literature was critically appraised and narratively synthesized to summarize current evidence, identify existing knowledge gaps, and discuss emerging technologies relevant to

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contemporary prosthodontic practice. The review was prepared in accordance with the **Scale for the Assessment of Narrative Review Articles (SANRA)** recommendations for narrative reviews, while a **PRISMA-style flow diagram** was included solely to illustrate the literature search and study selection process without implying a formal systematic review methodology.[16 17]

Table 1. Literature Search Strategy

Item	**Details**
Review Type	Evidence-Based Narrative Review
Reporting Guidance	Prepared according to SANRA recommendations for narrative reviews; literature selection illustrated using a PRISMA-style flow diagram
Databases	PubMed/MEDLINE, Scopus, Web of Science, Google Scholar
Search Period	January 2015 – June 2026
Language	English
Study Types Included	Systematic reviews, Meta-analyses, Randomized controlled trials, Prospective and retrospective clinical studies, Observational studies, Pilot studies, Consensus statements, Position papers, Clinically relevant narrative reviews
Keywords	Digital occlusion, Computerized occlusal analysis, T-Scan, OccluSense, Prosthodontics, CAD/CAM, Digital dentistry, Virtual articulator, Digital workflow, Artificial intelligence, Machine learning, Deep learning, Digital patient, Implant occlusion
Search Strategy	MeSH terms, free-text keywords, and Boolean operators (AND/OR)
Exclusion Criteria	Duplicate articles, Non-English publications, Editorials, Letters, Conference abstracts lacking adequate methodological information, Studies unrelated to prosthodontics

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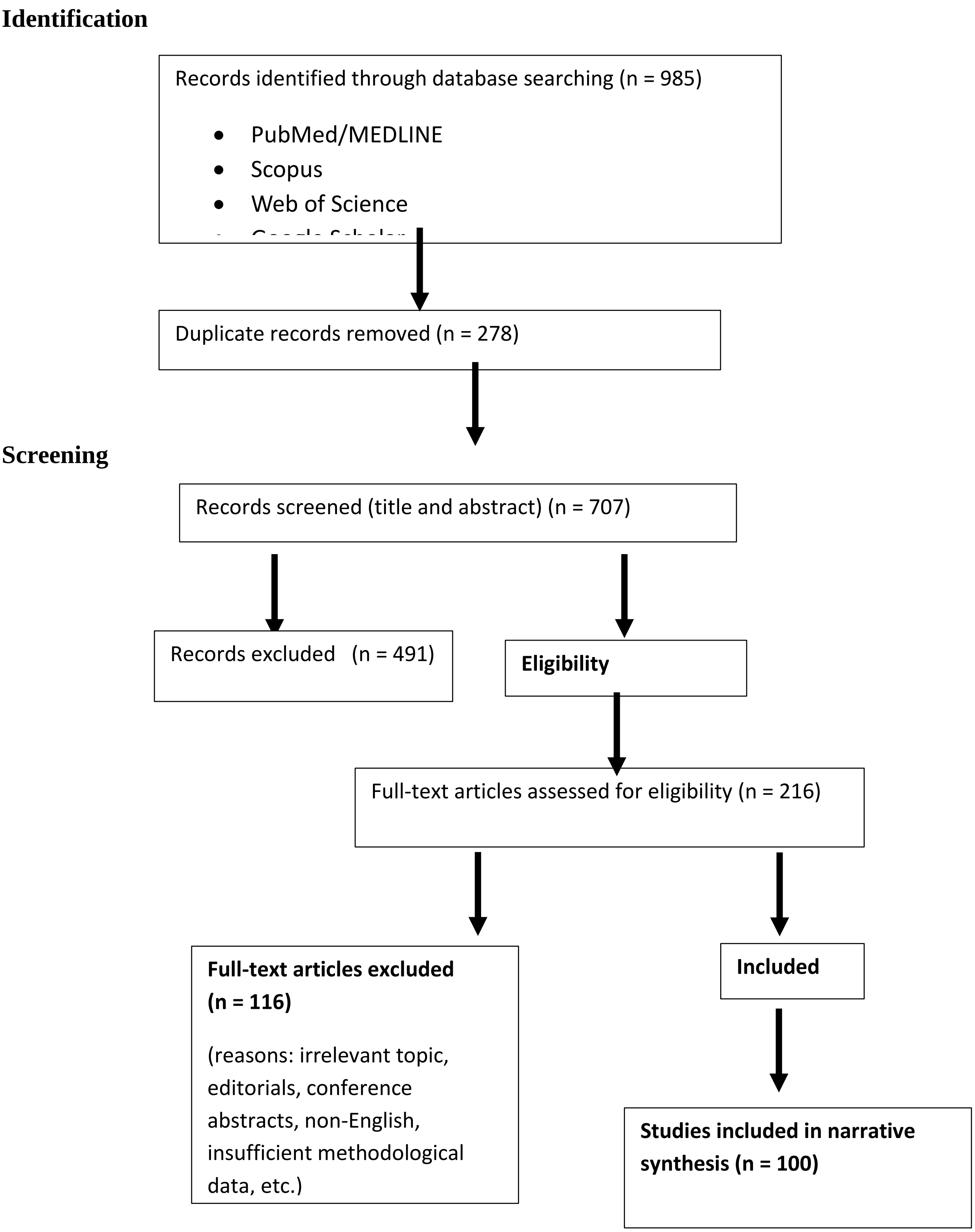
Figure 1. PRISMA-Style Flow Diagram for Literature Search and Study Selection



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3. Evolution of Occlusal Concepts and the Transition to Digital Occlusion

Occlusion has long been recognized as a cornerstone of successful prosthodontic rehabilitation. It encompasses the static and dynamic relationships between the maxillary and mandibular dentition and plays a critical role in mastication, speech, esthetics, temporomandibular joint (TMJ) function, and the longevity of prosthetic restorations.[1,2,18,] The establishment and maintenance of stable, harmonious occlusal relationships are therefore essential for achieving functional efficiency, biomechanical stability, and long-term clinical success in complete dentures, fixed dental prostheses, implant-supported restorations, and full-mouth rehabilitation.[1,2,18,19]

The concept of occlusion has evolved considerably over the past century in response to advances in prosthodontic philosophy, biomaterials, biomechanics, and clinical research. Early occlusal concepts were largely based on mechanical principles and anatomical observations, leading to the development of philosophies such as balanced occlusion, lingualized occlusion, mutually protected occlusion, and group function.[1,2,18,19,21] Each of these concepts was designed to optimize prosthesis stability, distribute occlusal forces appropriately, minimize harmful lateral forces, and preserve the health of the supporting oral tissues.[21] Although these principles continue to underpin contemporary prosthodontic practice, their successful clinical application has traditionally relied heavily on clinician experience and subjective interpretation of occlusal contacts.

For decades, conventional occlusal assessment has been performed using articulating paper, shimstock foil, wax occlusal records, pressure-indicating paste, and clinical examination. These techniques remain indispensable because they are inexpensive, readily available, and easy to incorporate into routine clinical practice.[3-5] However, they primarily provide qualitative information by identifying the location of occlusal contacts without objectively measuring the magnitude, timing, sequence, or distribution of occlusal forces. Consequently, interpretation is often influenced by operator experience, resulting in considerable inter- and intra-examiner variability and limiting diagnostic reproducibility.

The increasing complexity of contemporary prosthodontic rehabilitation has further exposed the limitations of conventional occlusal assessment. Modern treatment frequently involves implant-supported prostheses, monolithic ceramic restorations, CAD/CAM-fabricated restorations, immediate loading protocols, and comprehensive digital rehabilitation.[6,10-12] These procedures require a level of occlusal precision that conventional qualitative techniques cannot consistently provide. Even minor discrepancies in occlusal force distribution may contribute to complications such as ceramic chipping, prosthesis fracture, screw loosening, implant overload, occlusal instability, and patient discomfort. [10-12,22,23] Consequently, there is an increasing need for objective methods capable of quantifying functional occlusion rather than merely identifying contact locations.

The emergence of digital dentistry has fundamentally transformed prosthodontic practice by integrating advanced imaging technologies, computer-assisted design, and digital manufacturing into comprehensive clinical workflows. Technologies including intraoral scanners (IOS), cone-beam computed tomography (CBCT), facial scanners, CAD/CAM systems, virtual articulators, digital facebows, and patient-specific mandibular motion analysis enable highly accurate digital representation of the patient's oral environment.[13-15,25] These innovations have reduced cumulative procedural errors, enhanced communication between clinicians and dental laboratories, improved prosthesis accuracy, shortened treatment time, and increased workflow efficiency.

Within this rapidly evolving digital ecosystem, computerized occlusal analysis has emerged as one of the most significant advances in functional prosthodontic diagnosis. Unlike conventional qualitative techniques, computerized systems objectively record occlusal contact sequence, relative force distribution, contact timing, bilateral force balance, and dynamic mandibular movements in real time. These quantitative functional data enable clinicians to identify occlusal discrepancies more precisely, perform targeted occlusal adjustments, and monitor treatment outcomes with greater consistency and reproducibility. Technologies such as **T-Scan**, **OccluSense**, and other digital force-analysis systems have therefore become valuable adjuncts in contemporary prosthodontic practice.[13,25]

The evolution of digital prosthodontics has subsequently progressed beyond isolated digital devices toward fully integrated digital workflows. The combination of intraoral scanning, CAD/CAM fabrication, virtual articulators, digital jaw-motion recording, facial scanning, and patient-specific mandibular movement analysis allows clinicians to simulate functional occlusion within a virtual environment before prosthesis fabrication.[26-29]This comprehensive digital integration facilitates more accurate prosthetic design, minimizes chairside occlusal adjustments, enhances interdisciplinary communication, and supports individualized treatment planning.

More recently, artificial intelligence (AI) has emerged as the next frontier in digital prosthodontics. Machine learning and deep learning algorithms are increasingly being investigated for automated diagnosis, image interpretation, prosthesis design, treatment planning, prediction of occlusal discrepancies, optimization of digital workflows, and clinical decision support. [10-13,22] Although routine clinical implementation remains limited, AI has considerable potential to integrate large volumes of patient-specific data, recognize complex functional patterns, and assist clinicians in delivering more personalized, efficient, and evidence-based prosthodontic care.

The transition from conventional qualitative assessment to objective digital occlusion represents a paradigm shift in prosthodontics. Rather than replacing established occlusal principles, digital technologies complement traditional clinical knowledge by providing quantitative functional information that enhances diagnostic precision, treatment planning, prosthesis fabrication, occlusal adjustment, and long-term maintenance. Appreciating this evolution is fundamental to understanding the role of contemporary digital technologies and provides the conceptual foundation for the evidence presented in the subsequent sections of this review.

Table 2. Evolution of Occlusal Assessment in Prosthodontics (Refined)

Era	Major Development	Key Characteristics	Principal Limitations
Conventional Era	Articulating paper, shimstock foil, wax records, pressure-indicating materials	Simple, inexpensive, qualitative assessment of occlusal contacts	Subjective interpretation; inability to quantify force, timing, or dynamic occlusion
Digital Dentistry Era	Intraoral scanners, CBCT, CAD/CAM systems, virtual articulators	Improved diagnostic accuracy, digital workflows, enhanced clinician–laboratory communication	Higher equipment costs, learning curve, dependence on digital infrastructure
Digital Occlusion Era	Computerized occlusal analysis (T-Scan, OccluSense), digital force analysis	Quantitative assessment of occlusal force distribution, contact timing, and dynamic mandibular function	Need for standardized protocols, limited long-term clinical evidence, additional equipment costs
Intelligent Digital Era	Artificial intelligence, machine	Intelligent decision support, personalized	Limited clinical validation, ethical and

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	learning, predictive analytics, digital patient concepts	treatment planning, predictive occlusal analysis, workflow automation	regulatory concerns, data privacy, interoperability challenges

4. Conventional Occlusal Assessment in Prosthodontics: Principles, Techniques, and Limitations

Accurate occlusal assessment is a fundamental component of prosthodontic diagnosis, treatment planning, prosthesis fabrication, insertion, and long-term maintenance. The establishment of stable and harmonious occlusal contacts is essential for preserving stomatognathic function, maintaining patient comfort, minimizing biological and mechanical complications, and ensuring the longevity of prosthetic restorations.[2,3,21,23] Consequently, precise evaluation of occlusion has long been regarded as an indispensable step in successful prosthodontic rehabilitation.[1,23,29]

For decades, conventional occlusal assessment techniques have represented the clinical standard in both fixed and removable prosthodontics. These methods are inexpensive, simple to perform, readily available, and require minimal clinical armamentarium, making them indispensable in everyday dental practice.[1-6] Despite their widespread use, however, most conventional techniques provide predominantly qualitative information and rely heavily on clinician interpretation. As prosthodontic treatment has become increasingly sophisticated with the incorporation of implant-supported restorations, CAD/CAM prostheses, monolithic ceramic materials, and comprehensive digital workflows—the limitations of these traditional methods have become increasingly evident.[1-8,23,25,29,30]

4.1 Articulating Paper

Articulating paper remains the most widely used material for identifying occlusal contacts during prosthodontic procedures. It consists of pigment-coated strips that transfer color onto occluding surfaces during mandibular closure, thereby enabling visualization of contact locations.[5,6,30]

Its popularity stems from several practical advantages, including low cost, ease of use, widespread availability, and compatibility with virtually all restorative procedures. Clinically, articulating paper is routinely employed during crown insertion, fixed dental prosthesis cementation, implant prosthesis delivery, complete denture adjustment, occlusal equilibration, and full-mouth rehabilitation.[30,31]

Despite these advantages, articulating paper possesses significant diagnostic limitations. Numerous investigations have demonstrated that the size, intensity, or morphology of articulating paper marks does not reliably correlate with occlusal force magnitude. Large markings do not necessarily indicate heavy occlusal loading, whereas smaller markings may occasionally represent high-force contacts.[30-32] Furthermore, interpretation of paper markings is highly operator-dependent, resulting in considerable inter- and intra-examiner variability and reducing diagnostic reproducibility.

4.2 Shimstock Foil

Shimstock foil is an ultrathin metallic foil commonly used to verify the presence or absence of occlusal contact after articulating paper has identified potential contact areas. Owing to its minimal thickness, shimstock provides greater sensitivity for confirming occlusal contact than conventional marking materials.[5]

Clinically, shimstock is particularly valuable during adjustment of implant-supported restorations, definitive crowns, fixed dental prostheses, and occlusal equilibration procedures where precise contact verification is essential.

However, shimstock serves primarily as a binary indicator, confirming whether a contact exists without providing quantitative information regarding occlusal force magnitude, contact timing, force distribution, or dynamic mandibular function. Consequently, its diagnostic value remains limited when functional occlusal analysis is required.[5,33]

4.3 Wax Records and Pressure-Indicating Materials

Wax occlusal records have historically played a pivotal role in recording maxillomandibular relationships during complete denture fabrication and extensive prosthodontic rehabilitation. Likewise, pressure-indicating materials have traditionally been employed to detect areas of excessive tissue pressure beneath removable prostheses.[4-6,33-35]

Although these materials continue to facilitate numerous clinical procedures, their accuracy is influenced by distortion, temperature sensitivity, handling characteristics, material deformation, and operator technique. Reproducibility is therefore limited, particularly when repeated measurements or precise quantitative comparisons are required.[34,36] These shortcomings restrict their usefulness for evaluating functional occlusion in contemporary prosthodontics.

4.4 Clinical Examination

Clinical examination remains an essential component of comprehensive occlusal assessment and cannot be replaced by any single diagnostic technology. Evaluation typically includes visual inspection, assessment of mandibular movements, palpation of the masticatory muscles, examination of temporomandibular joint function, identification of occlusal wear facets, fremitus testing, mobility assessment, and analysis of patient-reported symptoms.[1-3,21]

Collectively, these findings provide valuable information regarding functional adaptation, occlusal stability, and overall stomatognathic health. Nevertheless, clinical examination alone cannot objectively quantify occlusal loading or characterize the dynamic distribution of occlusal forces during mandibular function, thereby limiting its diagnostic precision.[1,18,21,23]

4.5 Limitations of Conventional Occlusal Assessment

Despite decades of successful clinical application, conventional occlusal assessment methods share several inherent limitations that have become increasingly significant in modern prosthodontics.

First, these techniques provide predominantly qualitative information and are unable to quantify occlusal force magnitude.[36,37] Second, they cannot accurately determine the sequence or timing of occlusal contacts during mandibular closure or excursive movements.[38] Third, interpretation remains highly dependent on clinician experience, resulting in limited reproducibility and considerable operator variability.[38] Fourth, conventional methods are incapable of recording dynamic occlusal events occurring during mastication or functional mandibular movements.[38,39] Finally, documentation is often restricted to static clinical records, making objective comparison during follow-up appointments difficult.

These limitations are particularly relevant in implant prosthodontics, CAD/CAM-fabricated restorations, monolithic ceramic prostheses, and comprehensive full-mouth rehabilitation, where even minor occlusal discrepancies may adversely affect biomechanical performance, prosthesis longevity, and patient comfort.[38-41]

4.6 Need for Objective Digital Occlusal Assessment

The shortcomings of conventional occlusal assessment have stimulated the development of computerized occlusal analysis systems capable of providing quantitative, reproducible, and

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real-time evaluation of functional occlusion. Unlike traditional methods that merely identify contact locations, modern digital technologies objectively measure contact timing, relative force distribution, occlusal sequence, bilateral force balance, and dynamic mandibular movements.[38]

These objective functional parameters enable clinicians to identify premature contacts, detect occlusal interferences, optimize force distribution, and perform evidence-based occlusal adjustments with greater precision. Importantly, computerized occlusal analysis is not intended to replace comprehensive clinical examination or established prosthodontic principles. Rather, it complements conventional assessment by providing quantitative information that enhances diagnostic accuracy, supports clinical decision-making, and improves treatment predictability.

The evolution from qualitative occlusal assessment toward objective digital analysis represents a major step toward precision prosthodontics and provides the foundation for the subsequent discussion of computerized digital occlusal analysis.

Table 3. Comparison of Conventional Occlusal Assessment Methods (Refined)

Method	Principle	Clinical Advantages	Major Limitations
Articulating Paper	Marks occlusal contact locations	Inexpensive, simple, widely available, easy to use	Qualitative only; cannot quantify occlusal force, contact timing, or sequence
Shimstock Foil	Verifies the presence or absence of occlusal contact	Highly sensitive contact verification; useful for definitive restorations and implants	Binary assessment only; does not measure force magnitude or dynamic occlusion
Wax Records	Records maxillomandibular relationships	Useful during jaw relation procedures and complete denture fabrication	Susceptible to distortion, temperature sensitivity, and limited reproducibility
Pressure-Indicating Paste	Detects pressure areas beneath removable prostheses	Useful for denture adjustment and tissue pressure evaluation	Does not evaluate functional occlusion or occlusal force distribution

Clinical Examination	Visual and functional assessment of occlusion and stomatognathic system	Comprehensive evaluation incorporating patient symptoms and functional findings	Subjective; lacks quantitative assessment of force, timing, and dynamic occlusal function

5. Computerized Digital Occlusal Analysis: Principles, Technologies, and Clinical Applications

The transition from conventional qualitative occlusal assessment to objective digital analysis represents one of the most significant advances in contemporary prosthodontics. As prosthodontic rehabilitation has become increasingly dependent on digital workflows, clinicians require diagnostic tools capable of accurately evaluating functional occlusion rather than simply identifying static contact locations. Computerized digital occlusal analysis fulfills this need by providing quantitative, real-time assessment of occlusal force distribution, contact timing, occlusal sequence, and mandibular dynamics.[42]

Unlike traditional methods such as articulating paper, shimstock foil, and wax records, computerized occlusal analysis systems generate reproducible functional data that enable objective evaluation of occlusal relationships throughout mandibular movements.[5,33-35,37] These technologies have improved the precision of occlusal adjustment, facilitated evidence-based clinical decision-making, and enhanced documentation of treatment outcomes. Consequently, digital occlusal analysis has become an important adjunct in fixed prosthodontics, implant dentistry, removable prosthodontics, occlusal splint therapy, and comprehensive oral rehabilitation.

5.1 Principles of Computerized Occlusal Analysis

Computerized occlusal analysis is based on pressure-sensitive electronic sensors that record occlusal contacts during both static intercuspation and dynamic mandibular movements. During closure and functional excursions, the sensor continuously records the sequence, relative intensity, timing, and distribution of occlusal contacts.[9,14,30,33,43] Dedicated software converts these recordings into dynamic graphical displays and numerical data, allowing clinicians to objectively analyze occlusal function.

Compared with conventional qualitative techniques, computerized systems provide substantially more comprehensive information, including:[8,10,33,37,43]

- Occlusal contact sequence
- Relative occlusal force distribution
- Initial point of contact
- Occlusion time
- Disclusion time
- Bilateral force balance
- Center of force trajectory
- Functional mandibular movement patterns

These objective measurements facilitate the identification of premature contacts, occlusal interferences, force asymmetry, and functional abnormalities that may not be detected through conventional clinical examination alone. Consequently, computerized occlusal analysis improves diagnostic precision while reducing operator-dependent variability.

5.2 T-Scan System

The **T-Scan system** is the most extensively investigated and clinically validated computerized occlusal analysis system currently available. Since its introduction by Maness and colleagues in the late 1980s, successive generations of T-Scan technology have demonstrated improvements in sensor sensitivity, recording accuracy, software functionality, and clinical usability, making it the reference standard for digital occlusal assessment in prosthodontics.[6,33,43-46]

The system employs an ultra-thin pressure-sensitive electronic sensor positioned between the dental arches during mandibular closure and functional movements.[46] The sensor records relative occlusal force distribution and contact timing, while proprietary software displays these data as dynamic two-dimensional and three-dimensional visualizations, enabling real-time assessment of functional occlusion.

Current T-Scan software provides quantitative information regarding:

- Relative occlusal force distribution
- Initial contact location
- Center of force trajectory
- Occlusion time
- Disclusion time
- Functional contact sequence
- Bilateral force balance

These parameters facilitate precise occlusal adjustment during prosthodontic rehabilitation and have demonstrated clinical utility in fixed prosthodontics, implant-supported restorations, complete dentures, full-mouth rehabilitation, temporomandibular disorder (TMD) management, and occlusal splint therapy.

Clinical Advantages

Major advantages of the T-Scan system include[43,44]:

- Objective measurement of occlusal contacts
- Dynamic functional assessment
- High reproducibility
- Improved documentation of treatment outcomes
- Enhanced patient communication through visual feedback
- Quantitative monitoring before and after treatment
- Reduced chairside occlusal adjustment in selected clinical situations

Several clinical investigations suggest that T-Scan-guided occlusal adjustment improves force distribution and functional occlusal balance while reducing operator dependence. Nevertheless, the magnitude of these clinical benefits varies among studies, and further long-term randomized controlled trials remain necessary.

Limitations

Despite its advantages, several limitations should be considered[43,44,46]:

- High initial equipment cost
- Ongoing sensor replacement expenses
- Requirement for clinician training
- Learning curve in data interpretation
- Measurement of relative rather than absolute occlusal force
- Limited availability in routine clinical practice

Accordingly, T-Scan should be considered an adjunctive diagnostic tool that complements comprehensive clinical examination rather than replacing conventional prosthodontic principles.

5.3 OccluSense System

OccluSense represents a newer generation of computerized occlusal analysis that combines conventional articulating paper markings with electronic pressure-sensing technology. The

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system utilizes an ultra-thin disposable sensor capable of simultaneously recording digital occlusal information while leaving colored contact markings on the occlusal surfaces.[46-48]

This dual-function design enables direct correlation between visual contact locations and quantitative functional data, facilitating more accurate clinical interpretation and occlusal adjustment.

Compared with earlier computerized systems, OccluSense offers several practical advantages:

- Wireless operation
- Disposable pressure-sensitive sensors
- Simultaneous visual and digital contact recording
- User-friendly software interface
- Simplified incorporation into routine clinical practice

Although preliminary studies suggest promising clinical performance, current evidence remains limited compared with T-Scan. Most published investigations involve small sample sizes or short follow-up periods, highlighting the need for larger comparative clinical trials to establish its long-term diagnostic reliability and clinical effectiveness.

5.4 Emerging Digital Occlusal Technologies

Digital occlusal assessment continues to evolve beyond isolated force-analysis systems toward comprehensive digital ecosystems integrating multiple diagnostic technologies. Emerging innovations include:

- Digital jaw-tracking systems[51]
- Virtual articulators[52]
- Patient-specific mandibular motion recording[53]
- Digital facebows[54]
- Optical motion capture systems
- Three-dimensional mandibular kinematic analysis[55]

Rather than functioning independently, these technologies increasingly operate as integrated components of comprehensive digital workflows. Combined with intraoral scanners, CBCT imaging, facial scanning, and CAD/CAM systems, they enable virtual simulation of patient-specific occlusal function before definitive prosthesis fabrication.[28] Such integration enhances prosthesis design, reduces chairside adjustments, and supports individualized prosthodontic treatment planning.

5.5 Clinical Applications in Prosthodontics

Computerized occlusal analysis has demonstrated clinical utility across virtually every discipline of prosthodontics.[56]

Fixed Prosthodontics[57]

Applications include:

- Crown insertion
- Fixed partial denture adjustment
- Full-mouth rehabilitation
- Occlusal equilibration

Objective force analysis assists clinicians in achieving balanced occlusal contacts while minimizing prosthetic complications.

Implant Prosthodontics[58]

Because osseointegrated implants lack periodontal ligament proprioception, precise occlusal management is particularly important.

Clinical applications include:

- Implant force distribution analysis
- Prevention of implant overload
- Occlusal monitoring during maintenance
- Immediate loading protocols
- Full-arch implant rehabilitation

Digital force analysis may reduce mechanical complications such as screw loosening, veneer fracture, and excessive implant loading.

Complete Dentures[59]

Computerized occlusal analysis facilitates:

- Bilateral balanced occlusion
- Improved denture stability
- Functional occlusal adjustment
- Assessment of dynamic occlusal balance

Occlusal Splints and TMD[60-61]

Applications include:

- Identification of premature contacts
- Splint adjustment

- Monitoring treatment response
- Functional occlusal equilibration

Digital measurements provide objective support for comprehensive TMD management but should not be considered standalone diagnostic criteria.

Full-Mouth Rehabilitation[62]

In complex rehabilitative cases, computerized occlusal analysis assists clinicians in:

- Monitoring occlusal changes throughout treatment
- Sequential equilibration
- Evaluating bilateral force balance
- Long-term maintenance

Integration with digital workflows improves treatment predictability and facilitates documentation of functional outcomes.

5.6 Current Evidence

Current literature consistently demonstrates that computerized occlusal analysis provides greater objectivity and reproducibility than conventional qualitative methods. Systematic reviews and clinical studies have reported improved visualization of contact timing, force distribution, and dynamic occlusal relationships, allowing clinicians to perform more precise occlusal adjustments.

Nevertheless, the available evidence remains heterogeneous. Published studies vary considerably with respect to study design, sample size, patient populations, outcome measures, and duration of follow-up. Although encouraging findings have been reported in implant prosthodontics, fixed prosthodontics, complete dentures, and TMD management, relatively few high-quality multicenter randomized clinical trials have evaluated long-term patient-centered outcomes.[42-46]

Importantly, current evidence supports computerized occlusal analysis as an adjunctive diagnostic modality rather than a replacement for comprehensive clinical examination. Optimal treatment decisions continue to require integration of objective digital measurements with patient symptoms, functional assessment, prosthodontic principles, and clinician experience.

5.7 Advantages and Limitations

Advantages	Limitations
Objective and reproducible assessment	High initial equipment cost
Quantitative force analysis	Sensor replacement expenses

Dynamic recording of occlusal function	Learning curve in interpretation
Improved documentation	Relative rather than absolute force measurement
Enhanced patient communication	Limited long-term clinical evidence
Better treatment monitoring	Lack of standardized clinical protocols
Supports digital workflows	Variable interoperability among digital systems

Table 4. Comparison of Major Computerized Occlusal Analysis Systems

Feature	**T-Scan**	**OccluSense**
Recording principle	Pressure-sensitive electronic sensor	Pressure-sensitive sensor with color marking
Force analysis	Relative force distribution	Relative force distribution
Contact timing	Yes	Yes
Dynamic recording	Yes	Yes
Visual contact marking	No	Yes
Sensor type	Electronic reusable system with disposable sensors	Disposable wireless sensors
Clinical evidence	Extensive	Limited but growing
Current clinical status	Reference standard	Emerging technology

5.8 Future Directions

Future developments are expected to integrate computerized occlusal analysis with artificial intelligence, digital twins, virtual articulators, jaw-tracking systems, and comprehensive digital patient models. Such integration may enable automated interpretation of occlusal data, predictive analysis of prosthesis longevity, intelligent treatment planning, and personalized occlusal rehabilitation. However, widespread clinical implementation will require standardized validation protocols, improved interoperability among digital platforms, and robust prospective clinical evidence.[51-62]

Computerized digital occlusal analysis has transformed prosthodontic diagnostics by enabling objective, reproducible, and dynamic evaluation of occlusal function. Among currently available technologies, **T-Scan** remains the most extensively validated system,

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whereas **OccluSense** and other emerging platforms offer promising alternatives with improved workflow integration. Although these technologies significantly enhance diagnostic precision and treatment planning, they should complement not replace comprehensive clinical examination, sound prosthodontic principles, and clinician expertise. [43-50]Future integration with artificial intelligence and fully digital workflows is expected to further advance precision prosthodontics.

6. Digital Workflow in Contemporary Prosthodontics: Integration of Digital Technologies for Precision Occlusion

The rapid evolution of digital dentistry has fundamentally transformed contemporary prosthodontic practice by replacing conventional analogue procedures with integrated digital workflows.[14,15,27] Traditional workflows based on elastomeric impressions, gypsum casts, mechanical articulators, and manual laboratory procedures are increasingly being replaced by comprehensive digital systems that enable accurate acquisition, analysis, design, fabrication, and verification of prosthetic restorations.[63] These advances have improved diagnostic precision, treatment efficiency, interdisciplinary communication, and patient centered outcomes while minimizing cumulative errors associated with conventional techniques.

Digital workflows extend beyond prosthesis fabrication and encompass every stage of prosthodontic rehabilitation, including diagnosis, treatment planning, occlusal analysis, prosthesis design, manufacturing, insertion, and long-term maintenance.[27] By integrating patient-specific anatomical and functional information obtained from intraoral scanners, cone-beam computed tomography (CBCT), facial scanning, virtual articulators, jaw-motion recording systems, and computerized occlusal analysis, clinicians can evaluate both static and dynamic occlusion within a unified digital environment.[24] This comprehensive approach supports evidence-based decision-making and facilitates more predictable prosthodontic rehabilitation.

As digital technologies continue to evolve, contemporary prosthodontics is shifting toward fully integrated digital ecosystems in which diagnostic data, prosthesis design, manufacturing, and functional verification are interconnected. Such workflows not only improve prosthesis accuracy but also establish the foundation for personalized, precision-based prosthodontic care.

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6.1 Components of the Contemporary Digital Workflow

A modern digital prosthodontic workflow consists of several interconnected technologies that collectively create a seamless treatment pathway from diagnosis to long-term follow-up.[27] Unlike conventional approaches, where clinical and laboratory procedures are performed independently, digital workflows integrate multiple datasets into a unified virtual environment.

The principal components include:

- Digital patient data acquisition
- Intraoral scanning (IOS)
- Extraoral facial scanning
- Cone-beam computed tomography (CBCT)
- Digital jaw relation recording
- Virtual articulators
- Digital facebows and jaw-motion tracking
- CAD/CAM prosthesis design
- Computer-assisted manufacturing (CAM)
- Computerized digital occlusal analysis
- Clinical verification and maintenance

The integration of these technologies minimizes cumulative procedural errors, enhances communication between clinicians and laboratories, and improves overall treatment predictability.

6.2 Intraoral Scanners (IOS)

Intraoral scanners (IOS) have become the cornerstone of digital prosthodontics by replacing conventional elastomeric impression materials with highly accurate optical scanning systems. These devices generate precise three-dimensional digital representations of the dentition, implant scan bodies, and surrounding soft tissues, enabling immediate visualization and efficient digital communication with dental laboratories.[27,64,65]

Compared with conventional impressions, intraoral scanning offers several clinical advantages:

- Improved patient comfort
- Elimination of impression material distortion
- Immediate assessment of scan quality

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- Greater workflow efficiency
- Digital storage and retrieval of patient records
- Easy integration with CAD/CAM systems
- Reduced need for impression remakes
- Enhanced communication with laboratories

IOS technology is routinely employed in the fabrication of:

- Single crowns
- Fixed dental prostheses
- Implant-supported restorations
- Removable partial dentures
- Complete dentures
- Full-mouth rehabilitations

Despite these advantages, certain clinical situations remain challenging. Accuracy may be reduced in completely edentulous arches, extensive long-span restorations, deep subgingival finish lines, excessive saliva, limited mouth opening, and multiple implant restorations because of image stitching errors and reduced reference landmarks.[66] Consequently, careful case selection and adherence to recommended scanning protocols remain essential.

6.3 CAD/CAM Technology

Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) represent one of the most influential technological advances in restorative dentistry. Following digital data acquisition, specialized CAD software enables clinicians and dental technicians to design restorations with highly accurate anatomical morphology, proximal contacts, emergence profiles, and occlusal relationships.[66-71] These digital designs are subsequently manufactured using subtractive milling or additive manufacturing (three-dimensional printing).

Major clinical advantages of CAD/CAM technology include:[69,70,71]

- Improved marginal and internal fit
- Standardized prosthesis fabrication
- Reduced laboratory errors
- Shorter treatment time
- Enhanced esthetics
- Superior material consistency
- Excellent reproducibility

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- Digital archiving of prosthetic designs

When integrated with computerized occlusal analysis and virtual articulators, CAD/CAM systems permit optimization of occlusal morphology before prosthesis fabrication, thereby reducing chairside adjustments and improving functional outcomes.

6.4 Virtual Articulators

Virtual articulators are computerized simulations of conventional mechanical articulators that reproduce mandibular movements within a digital environment. They combine digital casts with jaw-relation records to evaluate static and dynamic occlusal relationships during prosthesis design.[52-55]

Compared with conventional articulators, virtual articulators provide several advantages:

- Three-dimensional visualization of occlusion
- Dynamic simulation of mandibular movements
- Identification of occlusal interferences
- Digital modification of occlusal morphology
- Improved communication between clinicians and laboratories
- Integration with CAD/CAM software
- Repeatable virtual analysis without physical casts

Modern patient-specific virtual articulators incorporate individualized mandibular movement recordings obtained from jaw-tracking devices, thereby improving simulation accuracy compared with average-value articulators.

6.5 Digital Facebows and Jaw-Motion Recording Systems

Conventional facebows transfer the spatial relationship between the maxillary arch and the hinge axis of the articulator. Digital facebows perform this function using optical scanning and digital registration technologies, simplifying clinical procedures while improving accuracy and reproducibility.[53-56]

Similarly, digital jaw-motion recording systems capture mandibular movements in three dimensions during functional activities such as opening, closing, protrusion, and lateral excursions.

These technologies provide valuable patient-specific information regarding:

- Condylar pathways
- Mandibular trajectories

- Functional jaw movements
- Occlusal dynamics
- Mandibular kinematics
- Hinge-axis relationships

Such information enables clinicians to reproduce functional mandibular movements more accurately during prosthesis design, thereby enhancing occlusal harmony and reducing post-insertion adjustments.

6.6 The Digital Patient Concept

The concept of the **Digital Patient** represents one of the most significant developments in contemporary prosthodontics. Rather than relying on isolated clinical records, the Digital Patient integrates multiple patient-specific datasets into a comprehensive virtual model capable of simulating prosthodontic treatment before clinical intervention.[27,56,72]

Typical components include:

- Intraoral scans
- Facial scans
- CBCT datasets
- Digital photographs
- Jaw-motion recordings
- Virtual articulators
- Computerized occlusal analysis
- Medical and dental records

This integrated digital environment enables simultaneous evaluation of esthetic, anatomical, functional, and occlusal parameters, facilitating individualized treatment planning and interdisciplinary collaboration.

6.7 Integration of Computerized Occlusal Analysis within the Digital Workflow

Computerized occlusal analysis becomes substantially more valuable when incorporated into a complete digital workflow rather than being used as an isolated diagnostic tool. Quantitative occlusal data can be integrated with digital impressions, virtual articulators, CAD software, and implant planning systems to create patient-specific prosthetic designs based on functional occlusion.[73]

Digital occlusal analysis may contribute to:

- CAD prosthesis design
- Virtual articulator programming
- Implant planning
- Digital smile design
- Full-mouth rehabilitation
- Occlusal adjustment protocols
- Maintenance and long-term monitoring

This integration enables clinicians to evaluate prosthetic function before definitive restoration delivery, thereby reducing chairside occlusal adjustments, improving functional predictability, and enhancing prosthesis longevity.

As digital ecosystems mature, continuous updating of patient-specific functional information may facilitate adaptive prosthodontic treatment planning throughout the patient's lifetime.

6.8 Clinical Benefits of Integrated Digital Workflows

Current evidence suggests that integrated digital workflows provide several important clinical advantages compared with conventional analogue techniques.[57,63,71-73]

These benefits include:

- Improved diagnostic accuracy
- Enhanced communication between clinicians and laboratories
- Greater prosthesis precision
- Reduced chairside adjustment time
- Fewer laboratory remakes
- Improved patient comfort and experience
- Better documentation and record storage
- Increased treatment predictability
- Improved long-term maintenance
- Enhanced interdisciplinary collaboration

These advantages are particularly relevant in implant prosthodontics, full-mouth rehabilitation, digitally guided occlusal reconstruction, and complex multidisciplinary treatment.

6.9 Current Evidence

Recent systematic reviews and clinical investigations indicate that digital workflows improve the accuracy and efficiency of prosthodontic rehabilitation while enhancing communication between clinicians and laboratories. Intraoral scanning and CAD/CAM technologies have demonstrated high accuracy for single-unit restorations and short-span fixed prostheses, whereas virtual articulators and jaw-motion analysis facilitate more individualized prosthesis design.[57,63,73]

However, evidence regarding complete integration of all digital technologies including computerized occlusal analysis, patient-specific mandibular motion, facial scanning, and artificial intelligence remains relatively limited. Most available studies evaluate individual components rather than comprehensive digital workflows, and considerable heterogeneity exists regarding study design, outcome measures, and follow-up duration. Consequently, additional multicenter randomized clinical trials are required to establish standardized protocols and determine long-term clinical effectiveness.

6.10 Current Challenges

Despite substantial technological progress, several barriers continue to limit the widespread implementation of fully digital prosthodontic workflows.[74]

Major challenges include:

- High initial investment costs
- Software licensing and maintenance expenses
- Variable interoperability among digital platforms
- Need for clinician education and training
- Steep learning curve
- Lack of standardized clinical protocols
- Limited long-term clinical evidence
- Data privacy and cybersecurity concerns
- Dependence on reliable digital infrastructure

Addressing these limitations will require collaboration among clinicians, engineers, software developers, manufacturers, and regulatory organizations to develop open digital standards and evidence-based clinical guidelines.

6.11 Future Perspectives

Future digital prosthodontic workflows are expected to integrate artificial intelligence, digital twins, cloud-based data management, intelligent virtual articulators, and real-time computerized occlusal analysis into unified digital ecosystems. Such systems may enable

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automated prosthesis design, predictive occlusal adjustment, personalized treatment planning, and continuous monitoring of prosthetic performance throughout the maintenance phase.

The convergence of digital imaging, functional occlusal analysis, and artificial intelligence is expected to transform prosthodontics from a predominantly restorative discipline into a predictive, preventive, and precision-oriented specialty.

Figure 2. Integrated Digital Workflow in Contemporary Prosthodontics

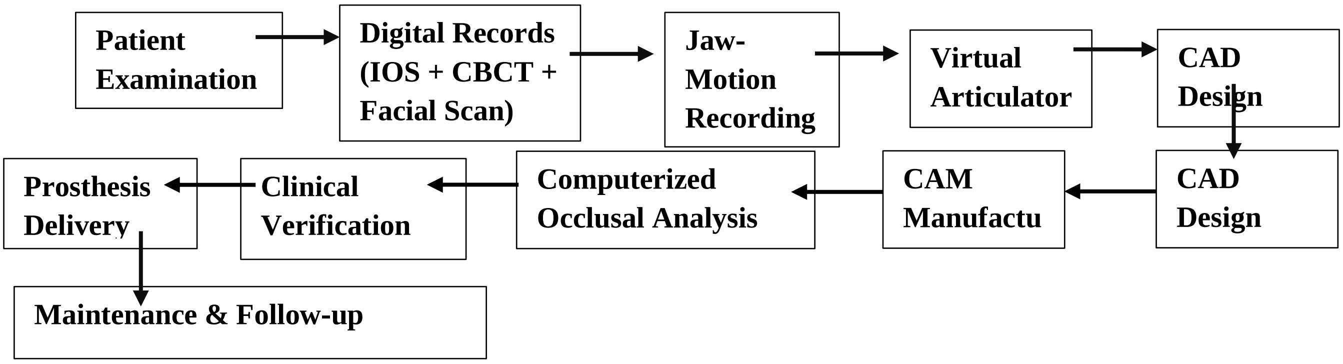

Table 5. Major Components of the Contemporary Digital Prosthodontic Workflow

Technology	Primary Function	Clinical Benefits	Limitations
Intraoral Scanner (IOS)	Digital impressions	Improved accuracy, patient comfort, efficient workflow	Reduced accuracy in extensive edentulous cases and long-span restorations
CBCT	Three-dimensional anatomical imaging	Implant planning, bone assessment	Radiation exposure, cost
CAD/CAM	Prosthesis design and fabrication	Precision, standardization, reduced laboratory errors	Equipment cost and technical expertise
Virtual Articulator	Dynamic occlusal simulation	Functional analysis, prosthesis optimization	Requires accurate digital records
Digital Facebow & Jaw Tracking	Patient-specific mandibular movement recording	Improved functional accuracy	Additional equipment and training
Computerized	Quantitative force	Objective occlusal	Learning curve, sensor

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Occlusal Analysis	and timing analysis	adjustment	replacement costs
Digital Patient Platform	Integration of all digital datasets	Comprehensive treatment planning	Software interoperability and data management

Integrated digital workflows have fundamentally transformed contemporary prosthodontics by combining intraoral scanning, CBCT, CAD/CAM technology, virtual articulators, jaw-motion analysis, and computerized occlusal analysis into a unified treatment pathway. These technologies improve diagnostic accuracy, prosthesis precision, communication, and clinical efficiency while supporting objective, evidence-based occlusal management. As artificial intelligence and digital patient technologies continue to evolve, fully integrated digital workflows are expected to become the foundation of precision prosthodontics.

7. Artificial Intelligence in Contemporary Prosthodontics and Digital Occlusion

Artificial intelligence (AI) has emerged as one of the most transformative innovations in digital healthcare and is rapidly reshaping contemporary prosthodontics. AI refers to computational systems capable of performing tasks that traditionally require human intelligence, including learning from data, recognizing complex patterns, interpreting clinical information, generating predictions, and supporting clinical decision-making. Recent advances in machine learning, deep learning, and computer vision have enabled AI to analyze large volumes of clinical, radiographic, and digital workflow data with remarkable speed and consistency.[13-15,27,57, 75]

In prosthodontics, AI is increasingly being integrated with digital technologies such as intraoral scanners (IOS), cone-beam computed tomography (CBCT), CAD/CAM systems, virtual articulators, digital facebows, jaw-motion recording devices, facial scanners, and computerized occlusal analysis systems. Together, these technologies are transforming traditional prosthodontic workflows into intelligent, data-driven systems capable of enhancing diagnostic accuracy, prosthesis design, treatment planning, and long-term maintenance.[24-26, 33]

Although AI has demonstrated considerable promise across several domains of prosthodontics, its application to digital occlusal analysis remains in an early stage of development. Most currently available evidence is based on proof-of-concept studies, retrospective investigations, and algorithm development rather than prospective clinical validation. Consequently, AI should presently be regarded as a powerful clinical decision-support tool that complements, rather than replaces, clinician expertise and evidence-based prosthodontic principles.

7.1 Fundamentals of Artificial Intelligence

Artificial intelligence encompasses several computational approaches that enable computers to analyze complex datasets, recognize patterns, generate predictions, and continuously improve performance through learning. Rather than following fixed programmed rules, AI systems learn from previously acquired data and identify relationships that may not be apparent through conventional statistical analysis.[14-16,75-77]

The principal AI technologies currently investigated in prosthodontics include:

- Machine Learning (ML)
- Deep Learning (DL)
- Artificial Neural Networks (ANN)
- Computer Vision
- Natural Language Processing (NLP)
- Predictive Analytics
- Reinforcement Learning

Machine learning algorithms develop predictive models by identifying relationships within large clinical datasets, whereas deep learning utilizes multilayer neural networks capable of recognizing highly complex anatomical and radiographic features with minimal human intervention. Computer vision enables automated interpretation of digital images, while predictive analytics estimates future clinical outcomes based on existing patient information.

These technologies collectively provide the computational foundation for intelligent digital prosthodontic workflows.

7.2 AI in Prosthodontic Diagnosis

One of the earliest and most successful applications of AI in prosthodontics has been automated diagnostic image interpretation.[79] Modern AI algorithms can analyze CBCT scans, intraoral scans, digital photographs, and radiographic images rapidly while reducing observer variability and improving diagnostic consistency.[27,74]

Recent investigations have demonstrated AI-assisted diagnosis in:

- Automated tooth segmentation

- Detection of missing teeth
- Identification of occlusal wear
- Margin evaluation of restorations
- Prosthesis assessment
- Implant treatment planning
- Bone quality and quantity assessment
- Identification of temporomandibular joint abnormalities
- Caries and periapical lesion detection
- Assessment of residual ridge morphology

By integrating information from multiple imaging modalities, AI systems may improve diagnostic efficiency while supporting more accurate prosthodontic treatment planning.

7.3 AI-Assisted Digital Occlusal Analysis

Computerized occlusal analysis generates large quantities of quantitative functional information that can be difficult to interpret using conventional visual assessment alone. Artificial intelligence has the potential to analyze these datasets automatically by identifying subtle functional patterns and predicting clinically significant occlusal abnormalities.[14-16,79,80]

Digital occlusal analysis records information regarding:

- Contact timing
- Relative force distribution
- Occlusal contact sequence
- Bilateral force balance
- Center of force trajectory
- Occlusion time
- Disclusion time
- Dynamic mandibular movements

AI-assisted interpretation may facilitate:

- Automatic detection of premature contacts
- Identification of occlusal interferences
- Recognition of asymmetric force distribution
- Prediction of implant overload
- Functional occlusal pattern recognition
- Automated occlusal reporting

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- Risk stratification for prosthetic complications
- Personalized occlusal adjustment recommendations

Such applications have the potential to reduce operator dependence, improve diagnostic consistency, and support evidence-based occlusal management. However, current clinical implementation remains limited because robust validation studies are still lacking.

7.4 AI in Digital Prosthesis Design

Conventional CAD software relies heavily on technician experience and manual design modifications. Artificial intelligence introduces adaptive prosthesis design by analyzing large datasets of previously successful restorations together with patient-specific anatomical and functional information[81].

AI-assisted CAD systems may analyze:

- Patient anatomy
- Existing dentition
- Functional occlusion
- Facial morphology
- Esthetic parameters
- Previous successful prosthetic designs
- Occlusal force distribution

Based on these analyses, AI may automatically propose:

- Crown morphology
- Occlusal anatomy
- Contact points
- Emergence profiles
- Pontic design
- Prosthesis contours
- Esthetic modifications

Although these systems substantially improve efficiency, the clinician remains responsible for reviewing, modifying, and approving all prosthetic designs before fabrication.

7.5 AI in Prosthodontic Treatment Planning

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Artificial intelligence is increasingly being investigated as an advanced clinical decision-support system capable of integrating multiple patient datasets into comprehensive treatment recommendations.[14,17,24,33,62,76-82]

By combining information from:

- CBCT imaging
- Intraoral scans
- Facial scans
- Digital photographs
- Jaw-motion recordings
- Occlusal records
- Medical and dental history

AI may assist clinicians in:

- Selecting appropriate prosthodontic treatment options
- Designing implant-supported restorations
- Predicting prosthesis longevity
- Estimating biomechanical complications
- Optimizing occlusal schemes
- Planning full-mouth rehabilitation
- Selecting restorative materials
- Predicting maintenance requirements

Rather than replacing clinician judgment, AI serves as an adjunct that supports evidence-based decision-making while improving efficiency and consistency.

7.6 AI and the Digital Patient

The concept of the **Digital Patient** provides an ideal platform for artificial intelligence because it integrates multiple sources of patient-specific information within a unified digital environment.[33,83]

AI can simultaneously analyze:

- CBCT datasets
- Intraoral scans
- Facial scans
- Digital photographs
- Jaw-motion recordings
- Virtual articulators

- Computerized occlusal analysis
- Medical history
- Previous prosthetic records

This integration enables comprehensive virtual treatment simulations before prosthesis fabrication while considering anatomical, esthetic, biomechanical, and functional variables simultaneously.

Future Digital Patient platforms may continuously update patient information throughout maintenance appointments, allowing AI algorithms to refine treatment recommendations dynamically and create adaptive digital models throughout the patient's lifetime.

7.7 Current Evidence

Current literature demonstrates encouraging progress in the application of AI to prosthodontics, particularly in image analysis, implant planning, automated prosthesis design, and diagnostic support. Several proof-of-concept investigations have reported excellent performance for specific image-analysis tasks, while commercial CAD platforms have begun incorporating AI-assisted design features into routine clinical workflows.[33]

Nevertheless, evidence supporting AI specifically for digital occlusal analysis remains limited. Most available studies are experimental, involve relatively small datasets, utilize retrospective data, or focus primarily on algorithm development rather than long-term clinical outcomes. Considerable heterogeneity also exists regarding datasets, validation methods, outcome measures, and reporting standards.

At present, there is insufficient high-quality clinical evidence to recommend AI as a replacement for clinician judgment or established prosthodontic protocols. Instead, AI should be regarded as an adjunctive technology that enhances diagnostic efficiency, improves workflow integration, and supports evidence-based clinical decision-making.

7.8 Limitations and Challenges

Despite its considerable promise, several challenges continue to limit the routine clinical implementation of artificial intelligence in prosthodontics.[84]

Major limitations include:

- Limited availability of large, high-quality annotated datasets
- Lack of standardized validation protocols
- Algorithm bias

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- Limited explainability ("black-box" decision making)
- Integration challenges among different digital platforms
- Regulatory and medico-legal considerations
- Ethical concerns
- Data privacy and cybersecurity issues
- High implementation costs
- Need for clinician education and training

Addressing these challenges will require close collaboration among prosthodontists, engineers, software developers, data scientists, manufacturers, and regulatory organizations.

7.9 Future Perspectives

Artificial intelligence is expected to become a central component of next-generation digital prosthodontics.[84]

Future developments may include:

- Real-time AI-guided occlusal adjustment
- Intelligent virtual articulators
- Predictive prosthesis longevity analysis
- AI-assisted digital smile design integrated with occlusal analysis
- Fully personalized prosthesis design
- Automated implant occlusion optimization
- Digital twin technology for prosthodontic simulation
- Cloud-based collaborative treatment planning
- Continuous monitoring of occlusal changes using wearable digital devices
- Adaptive maintenance protocols based on predictive analytics

As AI algorithms mature and stronger clinical evidence becomes available, these technologies are expected to contribute to more precise, efficient, personalized, and preventive prosthodontic care.

7.10 Clinical Implications

The integration of artificial intelligence into digital prosthodontics has the potential to improve every stage of prosthodontic rehabilitation—from diagnosis and treatment planning to prosthesis fabrication, occlusal adjustment, and long-term maintenance.[84]

Current evidence suggests that AI may improve:

- Diagnostic consistency
- Prosthesis design efficiency

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- Occlusal analysis
- Treatment planning
- Risk prediction
- Documentation
- Workflow automation
- Personalized patient care

Nevertheless, AI should continue to function as a clinical decision-support system rather than an autonomous decision-maker. Final diagnosis, treatment planning, and occlusal adjustment remain the responsibility of the prosthodontist.

Figure 3. Integration of Artificial Intelligence into the Digital Prosthodontic Workflow

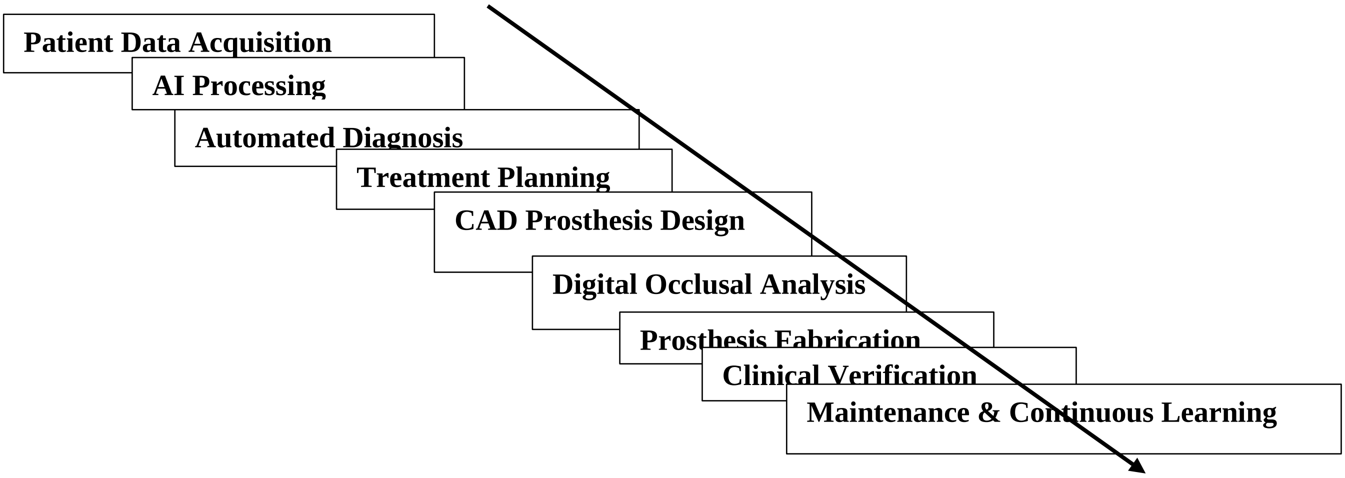

Table 6. Current and Emerging Applications of Artificial Intelligence in Prosthodontics

AI Application	Clinical Use	Potential Benefits	Current Limitations
Image Analysis	CBCT, IOS, radiographic interpretation	Faster diagnosis, improved consistency	Requires large annotated datasets
Prosthesis Design	AI-assisted CAD/CAM	Automated morphology, occlusal optimization	Clinician review remains essential
Digital Occlusal Analysis	Pattern recognition, force interpretation	Objective decision support, predictive occlusal analysis	Limited clinical validation
Treatment Planning	Clinical decision support	Personalized rehabilitation, risk prediction	Heterogeneous evidence

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Predictive Analytics	Prognosis and maintenance	Prediction of prosthesis longevity and complications	Limited long-term studies
Digital Patient Integration	Multi-modal data fusion	Comprehensive personalized treatment planning	Interoperability and data privacy challenges
Intelligent Virtual Articulators	Dynamic occlusal simulation	Patient-specific functional analysis	Experimental clinical evidence

Artificial intelligence is transforming digital prosthodontics by enabling intelligent interpretation of clinical data, enhancing prosthesis design, supporting computerized occlusal analysis, and improving personalized treatment planning. Although AI has demonstrated substantial promise, current evidence supports its use as an adjunct to not a replacement for clinical expertise. Future integration of AI with digital patient platforms, virtual articulators, digital twins, and predictive analytics is expected to define the next generation of precision prosthodontics.

8. Clinical Applications of Digital Occlusion in Contemporary Prosthodontics

The transition from conventional qualitative occlusal assessment to computerized digital occlusal analysis has substantially expanded the scope of prosthodontic diagnosis and treatment. Contemporary digital occlusion is no longer limited to identifying the location of occlusal contacts; rather, it enables quantitative evaluation of occlusal force distribution, contact timing, occlusal sequence, bilateral balance, and dynamic mandibular function. When integrated with intraoral scanning, CAD/CAM technology, virtual articulators, jaw-motion analysis, and digital workflows, computerized occlusal analysis facilitates evidence-based clinical decision-making throughout all stages of prosthodontic rehabilitation.[7-13,51]

Although digital occlusal systems should not replace comprehensive clinical examination, they provide objective functional information that complements conventional diagnostic methods. Their applications now extend across fixed and removable prosthodontics, implant dentistry, full-mouth rehabilitation, temporomandibular disorder management, and long-term maintenance, contributing to improved treatment precision and predictability.[51,56]

8.1 Fixed Prosthodontics

Successful fixed prosthodontic treatment depends on establishing stable and harmonious occlusal relationships following prosthesis insertion. Even minor occlusal discrepancies may result in excessive functional loading, ceramic chipping, restoration fracture, debonding, postoperative sensitivity, occlusal instability, or patient discomfort. Conventional methods such as articulating paper identify contact locations but cannot determine whether those contacts represent excessive occlusal forces or premature contact sequences.[10,11,15.57,68,82]

Computerized occlusal analysis provides objective assessment of occlusal force distribution and contact timing immediately after prosthesis placement. By identifying high-force contacts and functional interferences, clinicians can perform selective occlusal adjustments with greater precision while preserving healthy tooth structure and restorative materials. Digital recordings also allow comparison of occlusal changes before and after adjustment, improving treatment documentation and facilitating communication with patients and laboratory technicians.[41,68,70]

Several clinical investigations have reported that T-Scan-guided occlusal adjustment reduces unnecessary chairside corrections, improves bilateral force balance, and enhances patient comfort following delivery of crowns, fixed dental prostheses, veneers, and full-mouth restorations. Nevertheless, these systems should be used in conjunction with clinical examination, radiographic findings, and patient-reported symptoms to ensure comprehensive evaluation.[30,40,42,62]

Major clinical applications include:

- Single crowns
- Fixed partial dentures
- Veneers
- Occlusal equilibration
- Full-mouth fixed rehabilitation
- Post-cementation occlusal verification

8.2 Implant Prosthodontics

Occlusal management assumes even greater importance in implant-supported restorations because osseointegrated implants lack the periodontal ligament and therefore possess minimal physiologic shock absorption. Excessive occlusal loading may contribute to biological and mechanical complications including screw loosening, abutment fracture, prosthetic ceramic chipping, component fatigue, marginal bone loss, and implant overload.[3,12,19,23,32]

Computerized occlusal analysis enables objective evaluation of implant loading by quantifying relative occlusal force distribution during static and dynamic occlusion. Identification of excessive implant loading permits selective occlusal adjustment before complications develop, particularly during immediate loading protocols and full-arch implant rehabilitation.[40,41,62,79,82]

Digital occlusal analysis is particularly valuable during:

- Single implant crown insertion
- Implant-supported fixed partial dentures
- Full-arch implant prostheses
- Immediate loading procedures
- Occlusal monitoring during maintenance

Although digital systems cannot directly measure absolute occlusal forces, they provide reproducible relative force analysis that assists clinicians in establishing implant-protective occlusion and improving biomechanical stability.

8.3 Complete Denture Prosthodontics

Occlusion remains one of the principal determinants of complete denture stability, retention, masticatory efficiency, and patient satisfaction. Conventional denture adjustment often depends on repeated clinical corrections using articulating paper and clinician experience, making reproducibility difficult.[26,52,54]

Computerized occlusal analysis provides objective assessment of bilateral force distribution during maximum intercuspation and functional mandibular movements. Digital visualization of occlusal imbalance enables clinicians to perform more accurate selective grinding and achieve improved bilateral balanced occlusion.[59,69,73]

Clinical studies suggest that digital occlusal adjustment may improve:

- Denture stability
- Functional balance
- Masticatory efficiency
- Patient comfort
- Adaptation to new dentures
- Reduction in post-insertion adjustment visits

Although current evidence remains limited, computerized analysis represents a promising adjunct for complete denture occlusal refinement.

8.4 Removable Partial Dentures

Appropriate occlusal harmony is essential for preserving the health of abutment teeth and supporting tissues in removable partial dentures (RPDs). Premature occlusal contacts may generate excessive stresses that compromise clasp stability, accelerate wear of prosthetic components, and increase loading of periodontal structures.[32,52]

Computerized occlusal analysis assists clinicians by objectively identifying force concentration and occlusal imbalance, allowing selective adjustment before insertion and during maintenance appointments.[69] Potential clinical benefits include:

- Improved occlusal force distribution
- Reduced stress on abutment teeth
- Enhanced prosthesis stability
- Improved patient comfort
- Better long-term prosthesis longevity

Although published evidence remains relatively scarce compared with fixed prosthodontics, preliminary findings suggest beneficial clinical applications.

8.5 Full-Mouth Rehabilitation

Patients undergoing full-mouth rehabilitation frequently present with complex occlusal abnormalities including severe tooth wear, altered occlusal vertical dimension, loss of posterior support, multiple missing teeth, parafunctional habits, and compromised mandibular function. Such cases require meticulous occlusal planning throughout every phase of treatment.[1,2,24,27,51]

Computerized occlusal analysis enables clinicians to objectively monitor occlusal changes during provisionalization, definitive prosthesis delivery, and long-term follow-up. Integration with CAD/CAM systems and virtual articulators facilitates patient-specific occlusal refinement while reducing cumulative errors.[54,56,62,73]

Digital assessment allows evaluation of:

- Initial contact sequence
- Bilateral force balance
- Functional occlusal stability

- Force redistribution during treatment
- Final occlusal equilibration

Consequently, digital occlusal analysis contributes to more predictable rehabilitation while minimizing extensive chairside adjustments.

8.6 Occlusal Splint Therapy

Occlusal splints are widely used for managing bruxism, occlusal instability, and selected temporomandibular disorders. Successful splint therapy requires accurate distribution of occlusal contacts to minimize muscle hyperactivity and promote functional stability.[18,21,22,85-87]

Computerized occlusal analysis facilitates:

- Detection of premature contacts
- Objective splint adjustment
- Measurement of bilateral force balance
- Monitoring of treatment progress
- Evaluation of occlusal equilibration

By providing quantitative functional information, digital systems reduce operator variability and improve the precision of splint adjustment compared with conventional marking materials alone.

8.7 Temporomandibular Disorders (TMD)

Temporomandibular disorders are multifactorial conditions involving biological, behavioral, psychological, and biomechanical factors. While occlusion is no longer regarded as the sole etiological factor, occlusal abnormalities may contribute to symptoms in selected patients.[1,2,18,55,61]

Computerized occlusal analysis provides objective assessment of functional occlusal parameters including:

- Occlusion time
- Disclusion time
- Bilateral force balance
- Functional occlusal interferences
- Center of force trajectory

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Several clinical studies have demonstrated improvement in selected TMD symptoms following T-Scan-guided occlusal adjustment when incorporated into comprehensive management protocols. However, current evidence does not support the use of computerized occlusal analysis as an independent diagnostic test for TMD.[55,61] Rather, it should be considered an adjunct to clinical examination, imaging, patient history, and multidisciplinary management.

8.8 Maintenance and Long-Term Follow-up

One of the major advantages of computerized occlusal analysis is its ability to objectively monitor prosthetic function over time. Serial digital recordings allow clinicians to detect subtle functional changes that may not be apparent during conventional examination.[15,27,57]

Routine maintenance appointments may identify:

- Progressive occlusal wear
- Changes in force distribution
- Prosthesis settling
- Implant overload
- Occlusal instability
- Functional deterioration
- Development of premature contacts

Objective comparison of serial digital records facilitates evidence-based maintenance and supports timely intervention before biological or mechanical complications occur.[89.90]

8.9 Overall Clinical Benefits

Current evidence suggests that integrating computerized occlusal analysis into prosthodontic practice offers several clinically relevant advantages:

- Objective and reproducible occlusal assessment
- Quantitative evaluation of force distribution
- Dynamic analysis of mandibular function
- Improved prosthesis precision
- Reduced chairside adjustment time
- Better implant load management
- Enhanced clinical documentation
- Improved communication with patients and laboratory technicians

- Greater treatment predictability
- Support for evidence-based clinical decision-making

Despite these advantages, digital occlusal analysis should be regarded as a complementary diagnostic tool rather than a replacement for comprehensive clinical examination. Successful prosthodontic rehabilitation continues to depend upon sound biological principles, clinician expertise, patient-specific assessment, and careful interpretation of digital findings.

Table 7. Clinical Applications of Digital Occlusal Analysis in Contemporary Prosthodontics

Clinical Area	Primary Application	Principal Clinical Benefits
Fixed Prosthodontics	Crown and bridge adjustment	Improved occlusal precision, reduced chairside adjustments
Implant Prosthodontics	Implant force distribution	Prevention of overload, improved biomechanical stability
Complete Dentures	Bilateral balanced occlusion	Enhanced stability, comfort, and masticatory efficiency
Removable Partial Dentures	Occlusal harmonization	Protection of abutment teeth and improved prosthesis longevity
Full-Mouth Rehabilitation	Dynamic occlusal equilibration	Predictable rehabilitation and functional stability
Occlusal Splints	Functional occlusal adjustment	Improved splint balance and treatment monitoring
Temporomandibular Disorders	Dynamic functional assessment	Adjunctive support for comprehensive TMD management
Maintenance and Recall	Long-term occlusal monitoring	Early detection of functional changes and prosthetic complications

Computerized digital occlusal analysis has become an important adjunct in virtually every area of contemporary prosthodontics. By providing objective information regarding occlusal force distribution, contact timing, bilateral balance, and dynamic mandibular function, these technologies enhance diagnosis, treatment planning, prosthesis adjustment, and long-term maintenance. Their greatest clinical value is realized when integrated with comprehensive

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digital workflows and interpreted alongside sound prosthodontic principles and clinical judgment.

9. Current Challenges, Research Gaps, and Future Perspectives

The rapid evolution of digital dentistry has fundamentally transformed prosthodontic practice, shifting occlusal assessment from subjective clinical interpretation toward objective, quantitative, and technology-assisted evaluation. Computerized occlusal analysis systems, intraoral scanners (IOS), CAD/CAM technologies, virtual articulators, jaw-tracking devices, facial scanners, and artificial intelligence (AI) have collectively enhanced diagnostic precision, treatment planning, prosthesis fabrication, and long-term maintenance.[15,24,27,39,47,48,49,64,65,74] Despite these remarkable advances, the widespread implementation of digital occlusion in routine prosthodontic practice remains constrained by technological, clinical, educational, economic, and regulatory challenges.

Although current evidence supports the growing clinical value of digital occlusal analysis, important limitations continue to restrict its universal adoption. Furthermore, the available literature remains heterogeneous, with considerable variability in study design, clinical protocols, outcome measures, and follow-up duration. Consequently, many questions regarding the long-term effectiveness, cost-benefit ratio, and integration of digital technologies into comprehensive prosthodontic workflows remain unanswered. Addressing these issues will be essential for establishing standardized evidence-based protocols and realizing the full potential of precision prosthodontics.

9.1 Current Challenges

9.1.1 Lack of Standardization

One of the greatest barriers to widespread adoption of digital occlusal analysis is the absence of universally accepted clinical protocols. Commercial systems employ different sensor technologies, calibration methods, software algorithms, recording techniques, and data visualization formats, making comparisons between studies difficult.[11.27.42,74,] Likewise, no international consensus currently exists regarding ideal values for occlusion time, disclusion time, bilateral force distribution, or acceptable force asymmetry across different prosthodontic procedures.[11,27]

The absence of standardized terminology and reporting criteria further contributes to inconsistent interpretation of clinical findings.[27] Establishing internationally accepted guidelines would improve reproducibility, facilitate multicenter research, and enhance clinician confidence in digital occlusal assessment.

9.1.2 Limited High-Level Clinical Evidence

Although numerous observational studies, case series, pilot investigations, and systematic reviews suggest potential advantages of computerized occlusal analysis, relatively few well-designed randomized controlled clinical trials with long-term follow-up have been published.[40,42,54,61,63,71,82]

Current evidence is limited by considerable heterogeneity in:

- Study design
- Sample size
- Patient populations
- Prosthodontic treatment modalities
- Outcome measures
- Duration of follow-up

Consequently, definitive conclusions regarding the long-term clinical superiority of digital occlusal analysis over conventional techniques remain difficult. High-quality multicenter prospective clinical trials are therefore required to establish robust evidence-based recommendations.

9.1.3 Economic Considerations

The financial investment required for implementing digital occlusal technologies continues to represent a significant obstacle, particularly in developing countries, academic institutions with limited resources, and smaller private practices.[39,47-49]

Major cost-related considerations include:

- Initial equipment acquisition
- Software licensing fees
- Disposable sensor replacement
- Hardware maintenance
- Periodic software upgrades
- Staff training and continuing education

Although digital workflows may improve efficiency and reduce clinical adjustments, comprehensive cost-effectiveness analyses evaluating long-term economic benefits remain scarce.

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9.1.4 Learning Curve and Educational Requirements

Successful implementation of computerized occlusal analysis requires clinicians to develop competencies beyond conventional prosthodontic training. Appropriate interpretation of digital recordings depends on understanding sensor positioning, software operation, occlusal biomechanics, and quantitative data analysis.[92-94]

Without structured education and adequate clinical experience, digital information may be misinterpreted, potentially leading to inappropriate occlusal adjustments. Integration of digital occlusion into undergraduate curricula, postgraduate education, and continuing professional development programs will therefore be essential for maximizing clinical effectiveness.[92-94]

9.1.5 Technology Integration and Interoperability

Although digital dentistry continues to advance rapidly, many technologies remain isolated within proprietary software ecosystems.[94-96]

Current challenges include:

- Limited interoperability between different manufacturers
- Proprietary file formats
- Software incompatibility
- Inefficient data exchange
- Fragmented digital workflows

Future progress will depend upon open digital standards that enable seamless integration of intraoral scanners, CBCT, facial scanners, virtual articulators, jaw-tracking systems, computerized occlusal analysis, CAD/CAM platforms, and AI-based software within a unified digital environment.

9.2 Research Gaps

Despite substantial technological progress, several important knowledge gaps remain.

Gap 1: Long-Term Clinical Outcomes

Few multicenter randomized clinical trials have evaluated whether computerized occlusal analysis improves long-term prosthodontic outcomes compared with conventional occlusal assessment.[11,15,27,39,62,63]

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Gap 2: Implant Prosthodontic Evidence

Current evidence remains insufficient regarding the influence of digital occlusal analysis on:[30,32,40,41,58,79,82]

- Implant survival
- Marginal bone stability
- Prosthesis longevity
- Mechanical complications
- Biological complications
- Patient satisfaction

Gap 3: Comparative Evaluation of Digital Systems

Most available research focuses on the T-Scan system, while comparatively fewer studies have evaluated newer technologies such as OccluSense and other emerging digital occlusal analysis systems. Well-designed head-to-head comparative studies are required.[5,7,25,37,39,47,48,49,50]

Gap 4: Integrated Digital Workflows

Most published investigations examine individual technologies independently. Relatively few studies have evaluated comprehensive digital workflows integrating:[10,24,27,28,51,54,57,64-67,73,74]

- Intraoral scanners
- CAD/CAM
- Virtual articulators
- Jaw-motion tracking
- Facial scanning
- Computerized occlusal analysis
- Artificial intelligence

within a single patient-centered treatment protocol.

Gap 5: Artificial Intelligence Validation

Although AI demonstrates considerable promise in prosthodontic diagnosis and digital workflow optimization, clinical validation remains limited.[71,75,78-84]

Future studies should investigate AI-assisted:

- Occlusal diagnosis

- Force interpretation
- Treatment planning
- Prosthesis design
- Predictive maintenance
- Automated clinical decision support using large multicenter datasets.

Gap 6: Standardized Outcome Measures

The absence of standardized outcome measures limits comparison among published studies. International consensus regarding objective clinical parameters and patient-reported outcomes would substantially strengthen future evidence.[22,28,39,42,51,61]

Gap 7: Cost-Effectiveness and Patient-Reported Outcomes

Few investigations have assessed the economic impact of digital occlusal technologies or incorporated patient-reported outcome measures (PROMs) evaluating comfort, quality of life, masticatory efficiency, and overall treatment satisfaction.[15,27,57,62,63]

9.3 Future Perspectives

The future of digital occlusion is expected to extend beyond isolated diagnostic technologies toward intelligent, interconnected, and patient-specific digital ecosystems.

Artificial Intelligence

AI is likely to become an integral component of digital prosthodontics by enabling:[71,75,78-84]

- Automated occlusal diagnosis
- Intelligent interpretation of force distribution
- Predictive prosthesis design
- AI-assisted treatment planning
- Personalized occlusal adjustment recommendations
- Clinical decision-support systems

Rather than replacing clinician expertise, AI is expected to enhance diagnostic consistency, improve efficiency, and facilitate evidence-based decision-making.

Digital Twin Technology

Digital twin technology represents one of the most promising future developments in prosthodontics. A digital twin is a dynamic virtual representation of an individual patient that continuously integrates anatomical, functional, and biomechanical information.[67,78,80-82]

Future digital twins may simulate:

- Occlusal loading
- Implant biomechanics
- Prosthesis performance
- Functional mandibular movements
- Long-term wear patterns
- Treatment outcomes

before definitive prosthesis fabrication, allowing clinicians to optimize treatment plans in a completely virtual environment.

Intelligent Virtual Articulators

Next-generation virtual articulators are expected to integrate:[24,51,54,73]

- Patient-specific jaw-motion recordings
- Computerized occlusal analysis
- Facial scanning
- Electromyographic data
- AI-driven predictive algorithms
- Dynamic muscle simulation

This evolution will provide more physiologic simulation of mandibular function than conventional articulators based on average anatomical values.

Cloud-Based Digital Prosthodontics

Cloud computing has the potential to enhance collaboration among clinicians, laboratories, and specialists by enabling:[27,64,74]

- Secure storage of digital patient records
- Remote consultations
- Real-time interdisciplinary communication
- Cloud-based prosthesis design
- Continuous patient monitoring
- Multi-center collaborative treatment planning

Such digital ecosystems may improve treatment efficiency while facilitating evidence-based clinical practice.

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Precision Prosthodontics

Future prosthodontic rehabilitation is expected to become increasingly personalized through integration of:[67,71,75,78-84]

- Digital patient models
- Occlusal biomechanics
- AI-assisted diagnosis
- Predictive analytics
- Genomic and biomarker information
- Continuous functional monitoring

This emerging concept of **precision prosthodontics** aims to deliver individualized, predictive, preventive, and data-driven rehabilitation tailored to each patient's unique anatomical and functional characteristics.

9.4 Clinical Recommendations

Based on the currently available evidence, the following recommendations may facilitate the successful implementation of digital occlusion in contemporary prosthodontic practice:

- Use computerized digital occlusal analysis as an adjunct to—not a replacement for—comprehensive clinical examination and sound prosthodontic principles.
- Integrate digital occlusal analysis within a complete digital workflow whenever feasible, including intraoral scanning, CAD/CAM systems, and virtual articulators.
- Employ standardized recording protocols to improve reproducibility and facilitate longitudinal comparisons.
- Interpret digital findings in conjunction with patient symptoms, clinical examination, radiographic assessment, and functional analysis before undertaking irreversible occlusal adjustments.
- Encourage continuing professional education and structured training in digital prosthodontic technologies.
- Promote multicenter collaborative research using standardized methodologies and validated outcome measures.
- Incorporate patient-reported outcome measures and cost-effectiveness analyses into future clinical investigations to better assess the real-world impact of digital occlusal technologies.

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Table 8. Current Challenges and Proposed Solutions

Challenge	Clinical Impact	Proposed Solution
Lack of standardized protocols	Variable diagnosis and treatment outcomes	International consensus guidelines and standardized reporting criteria
Limited high-quality clinical evidence	Reduced confidence in recommendations	Multicenter randomized controlled clinical trials with long-term follow-up
High equipment and maintenance costs	Limited adoption in routine practice	Cost-effectiveness studies, wider technology availability, and reduced hardware costs
Learning curve	Variable interpretation and inconsistent clinical application	Structured undergraduate, postgraduate, and continuing education programs
Poor interoperability	Fragmented digital workflows	Open digital standards and cross-platform software integration
Limited AI validation	Restricted routine clinical implementation	Large-scale prospective validation studies and regulatory frameworks

Table 9. Major Research Gaps Identified

Research Gap	Priority
Long-term multicenter randomized clinical trials	Very High
Implant prosthodontic outcomes	High
AI-assisted digital occlusal diagnosis	High
Integration of multiple digital technologies	High
Cost-effectiveness analyses	Moderate
Standardized clinical outcome measures	Very High
Patient-reported outcome measures (PROMs)	Moderate

Digital occlusal analysis has evolved from an emerging diagnostic technology into a fundamental component of contemporary digital prosthodontics. Nevertheless, broader clinical implementation requires stronger scientific evidence, standardized clinical protocols, improved interoperability, comprehensive clinician training, and cost-effective integration into routine practice. Future convergence of artificial intelligence, digital twin technology, intelligent virtual articulators, cloud-based digital ecosystems, and precision prosthodontics is expected to transform digital occlusion into a personalized, predictive, and evidence-driven approach to prosthodontic rehabilitation.[96-101]

10. Conclusion

The evolution of digital dentistry has fundamentally transformed the assessment and management of occlusion in contemporary prosthodontics. Traditional qualitative methods, including articulating paper, shimstock foil, and wax records, continue to serve as valuable clinical tools because of their simplicity, accessibility, and low cost. However, their inability to provide objective information regarding occlusal force magnitude, contact timing, and dynamic mandibular function has limited their capacity to meet the precision demands of modern prosthodontic rehabilitation. The introduction of computerized digital occlusal analysis has addressed many of these shortcomings by enabling quantitative, reproducible, and real-time evaluation of occlusal function, thereby supporting more accurate diagnosis, treatment planning, occlusal adjustment, and long-term maintenance.

Among currently available technologies, computerized occlusal analysis systems—particularly the T-Scan system—have demonstrated the greatest clinical validation for assessing occlusal force distribution, contact sequence, occlusion time, and disclusion time. Emerging systems such as OccluSense and other digital force-analysis technologies further expand the available options while offering improved workflow integration and user convenience. Nevertheless, the available evidence consistently indicates that these technologies should be regarded as adjuncts to comprehensive clinical examination rather than replacements for sound prosthodontic principles and clinician judgment.

The integration of computerized occlusal analysis with contemporary digital workflows—including intraoral scanning, CAD/CAM technology, virtual articulators, digital facebows, jaw-tracking systems, and the digital patient concept—has significantly enhanced prosthodontic precision. By combining anatomical, functional, and biomechanical information within a unified digital environment, clinicians can improve communication with dental laboratories, reduce cumulative procedural errors, minimize chairside adjustments, and achieve more predictable restorative outcomes. This integrated approach represents a major step toward precision prosthodontics and patient-specific rehabilitation.

Artificial intelligence represents the next phase in the evolution of digital prosthodontics. Although current applications remain largely investigational, AI has demonstrated considerable potential for automated image analysis, prosthesis design, treatment planning, predictive analytics, and intelligent interpretation of digital occlusal data. As larger clinical datasets become available and validation studies mature, AI-assisted systems may enhance diagnostic consistency, optimize prosthodontic workflows, and facilitate personalized occlusal management. Future developments such as digital twin technology, intelligent virtual articulators, cloud-based digital ecosystems, and predictive biomechanical modeling are expected to further advance evidence-based prosthodontic care.

Despite these technological advances, several important challenges remain. The absence of standardized clinical protocols, limited high-quality long-term clinical evidence, high implementation costs, software interoperability issues, learning curve associated with digital technologies, and insufficient validation of emerging AI applications continue to limit widespread clinical adoption. Addressing these limitations through international consensus guidelines, multicenter randomized clinical trials, standardized outcome measures, clinician education, and cost-effectiveness research will be essential for establishing stronger evidence-based recommendations.

Overall, digital occlusion has evolved from a supplementary diagnostic innovation into a central component of contemporary prosthodontics. The convergence of computerized occlusal analysis, comprehensive digital workflows, and artificial intelligence is progressively transforming prosthodontic rehabilitation from a predominantly experience-based discipline toward a more objective, data-driven, and patient-centered specialty. Continued technological innovation, coupled with rigorous clinical research and standardized implementation strategies, is expected to further improve diagnostic precision, functional outcomes, prosthesis longevity, and patient satisfaction, ultimately shaping the future of precision prosthodontics.

Digital occlusal analysis has emerged as a valuable adjunct in contemporary prosthodontics by providing objective assessment of occlusal function and enhancing the accuracy of diagnosis, treatment planning, prosthesis fabrication, and maintenance. When integrated with digital workflows and supported by clinician expertise, these technologies offer a more predictable, evidence-based, and patient-centered approach to prosthodontic rehabilitation. Future integration with artificial intelligence and advanced digital ecosystems is expected to further refine precision occlusion and redefine the standard of prosthodontic care.

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Author Contributions

Dr. Raman Kumar conceived the review topic, performed the literature search, critically analyzed the published evidence, interpreted the findings, prepared the manuscript, revised the content, and approved the final version of the manuscript.

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