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AI Driven Prosthetic Design and Workflow in Prosthodontics: Designing Smarter via AI-Driven CAD/CAM Designs and Functional Analysis (A Review)

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Abstract: Background: Artificial Intelligence (AI) is transforming prosthodontics by streamlining workflows from diagnosis to dental restoration fabrication. Machine learning (ML) and deep learning (DL) have revolutionised various industries by significantly enhancing both precision and efficiency. Unlike traditional approaches that rely heavily on manual labour and time-consuming processes, these advanced technologies facilitate highly automated workflows. For instance, AI-driven computer-aided design (CAD) software such as 3Shape Automate and Exocad Dental CAD exemplifies this innovation by achieving an impressive accuracy rate of over 97% in crown preparation. Moreover, these sophisticated tools can drastically streamline the design process, reducing the time required for creation by an astonishing 75% to 90%. Additionally, they incorporate features like occlusal and functional analysis through virtual articulators, which allows users to predict and identify potential issues before the milling stage. This not only improves overall product quality but also enhances the efficiency of the design-to-production pipeline in the dental field. AI improves data acquisition by removing artefacts from scans and monitors restorations during use for optimal performance. Additionally, machine learning can predict wear patterns of materials, aiding in selecting durable options. Research shows that AI-assisted dentures improve occlusal balance by 30% compared to traditional methods, demonstrating AI's significant impact on efficiency and patient care in prosthodontics.

Keywords: Artificial intelligence (AI), Convolutional Neural Networks (CNN), Computer-Aided Design (CAD) & Computer-Aided Manufacturing (CAM), Digital Dentistry.

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INTRODUCTION

Artificial intelligence (AI) is transforming prosthodontics by enhancing precision, efficiency, and clinical outcomes. Its evolution from rule-based systems to advanced deep learning algorithms has significantly changed dental practices. AI integration with computer-aided design and manufacturing (CAD/CAM) automates the creation of high-precision prosthetics, improves digital impressions, and streamlines workflows.1,2 The history of AI in dentistry dates back to the 1950s with systems designed to mimic human reasoning. With the rise of machine learning in the 1980s, algorithms now identify patterns in large datasets, aiding in predictive modeling.3 Recent advances in deep learning have improved image analysis, vital for recognizing dental anatomy and interpreting cone-beam computed tomography (CBCT) scans. Currently, narrow AI technologies focus on tasks such as CAD/CAM design and tooth preparation, significantly impacting areas like diagnosis and treatment planning. Automated radiograph interpretation assists in detecting caries and evaluating periodontal conditions, while AI-driven predictive models help forecast restorative procedure outcomes, enhancing both durability and aesthetics.4 In design and fabrication, AI accelerates tooth preparation and improves the fitting of restorations, reducing material waste. In implantology, AI systems enhance placement accuracy, lowering complications and improving prosthetic fit. The collaboration between AI and CAD/CAM is reshaping prosthetic workflows, with real-time analysis improving impression accuracy and minimizing errors, leading to more stable restorations like CAD/CAM crowns. Overall, AI's integration in prosthodontics is making procedures more efficient and outcomes more predictable.5 This review in an attempt to explore various AI driven prosthetic designs and Workflow which enables smarter designing via AI-Driven CAD/CAM designs and functional/occlusal analysis.

Methods of Literature Search

This literature review effectively examines various online search engines, including Google, Google Scholar, and Yahoo, as well as key academic databases such as PubMed, PubMed Central, Medline Plus, Cochrane, Medknow, EBSCO, Science Direct, HINARI, INDMED, and Embase. We strategically focused on Medical Subject Headings (MeSH) and essential keywords related to dentistry and prosthodontics, specifically targeting terms such as Artificial Intelligence (AI), Convolutional Neural Networks (CNN), Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), and Digital Dentistry. We rigorously limited our search to articles published in English, Chinese, Portuguese, Spanish, and Korean, while emphasising English-language articles from the last 15 years. Our goal was to gather high-quality sources, including systematic reviews, meta-analyses, and clinical guidelines published in reputable dental journals. Initially, we identified 85 articles. After a thorough refinement process, we confidently narrowed this number to 40 articles that met our inclusion criteria and were highly relevant to our review objectives. This refinement focused exclusively on selecting review articles and eliminating other study types, such as meta-analyses and original research.

ARTIFICIAL INTELLIGENCE

Artificial intelligence (AI) encompasses a range of sophisticated computer systems and machines designed to undertake tasks that traditionally necessitate human intelligence. These tasks include, but are not limited to, learning from experiences, reasoning through complex scenarios, solving intricate problems, perceiving their environment, and comprehending human language. As a dynamic branch of computer science, AI focuses on the creation and development of systems that can execute complex functions—mirroring the cognitive capabilities of humans.[6,7] By leveraging and analyzing extensive datasets, AI systems are able to identify patterns and trends, which empower them to make

informed predictions, decisions, and recommendations. This capability marks a significant advancement in technology, enabling machines to operate with a level of autonomy that was previously thought to be the domain of human intellect.[8]

THE INTEGRATION OF ARTIFICIAL INTELLIGENCE WITHIN THE FIELD OF PROSTHODONTICS

Artificial intelligence (AI) is revolutionizing the field of prosthodontics by improving diagnostic accuracy, optimizing workflows in computer-aided design and manufacturing (CAD/CAM), and tailoring treatment plans for individual patients. In fixed prosthodontics, AI plays a crucial role in various applications.[9] For instance, it enhances CAD/CAM and restoration design by accurately identifying tooth preparation margins, achieving an impressive accuracy rate of 97.4% in automating the tracing of finish lines. Additionally, machine learning algorithms streamline shade selection by analyzing tooth images and colorimetric data to recommend precise shades, surpassing traditional visual methods.[10] AI also contributes to Digital Smile Design (DSD) by assessing facial symmetry, lip lines, and tooth shapes to create photorealistic simulations that help patients envisage their future smiles. In the realm of removable prosthodontics, AI improves framework design by classifying edentulous arches using Kennedy classifications and suggesting optimal designs for removable partial denture (RPD) frameworks. Furthermore, AI's deep learning models can predict facial soft-tissue changes after patients receive complete dentures, allowing for better planning and expectations. In implantology, AI is enhancing surgical planning by analysing cone beam computed tomography (CBCT) scans to assess bone quality and density.[11] This information helps clinicians determine the optimal placement, angle, and size of implants. Additionally, convolutional neural networks (CNNs) are highly effective at identifying and classifying various dental implant systems from radiographs, achieving a pooled accuracy of approximately 95.6%. Overall, the integration of AI in prosthodontics improves clinical outcomes and patient satisfaction by providing greater precision and personalised care.[12]

ADVANCEMENTS IN ARTIFICIAL INTELLIGENCE APPLICATIONS IN IMPLANTOLOGY

Artificial intelligence (AI) is revolutionizing the field of implant dentistry by streamlining and enhancing various processes. It automates intricate diagnostic tasks, allowing for faster and more accurate assessments of patients' needs. AI significantly improves the precision of surgical planning, ensuring that each procedure is tailored to the unique anatomy and conditions of the patient.[13] Furthermore, it facilitates real-time intraoperative guidance through advanced robotics, helping surgeons navigate with increased accuracy during procedures. Current applications of AI extend throughout the entire digital workflow, beginning with the meticulous creation of a virtual patient model that simulates individual circumstances and continuing through to comprehensive long-term post-operative monitoring. This holistic integration of technology not only elevates the standard of care but also enhances overall patient outcomes.[14]

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INTEGRATING ARTIFICIAL INTELLIGENCE INTO CAD/CAM DESIGN PROCESSES

The integration of Artificial Intelligence (AI) in Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) significantly revolutionizes the design process by automating repetitive tasks, facilitating generative design, and improving accuracy throughout the workflow. AI algorithms are capable of analyzing vast amounts of data, allowing them to produce numerous design alternatives based on specific parameters and constraints.[15] This generative design process not only optimizes for factors like material strength and weight but also accounts for cost-effectiveness and manufacturability, ultimately leading to innovative solutions that meet precise project requirements. In many cases, the time required to complete a design can be reduced by over 50%, thereby enhancing overall productivity in various manufacturing and engineering sectors.[16] Moreover, AI acts as an intelligent assistant across the entire design-to-manufacturing pipeline. It streamlines workflows by providing real-time feedback and insights, enabling designers and engineers to make informed decisions quickly. By automating routine tasks such as part modelling, simulation, and analysis, AI allows professionals to focus more on creative problem-solving and strategic thinking. This shift not only accelerates the development cycle but also enhances the quality of the final product, paving the way for more efficient and innovative manufacturing solutions.[17]

UTILIZATION OF ARTIFICIAL INTELLIGENCE IN OCCLUSAL ANALYSIS

The integration of artificial intelligence (AI) in prosthodontic occlusal analysis significantly enhances the precision of treatment outcomes by automating the interpretation of digital scans. Advanced AI systems have achieved an impressive accuracy rate of 90% to 96% in classifying different types of occlusion. This high level of accuracy allows for a more reliable assessment of a patient's biting and chewing patterns.[18] Furthermore, AI plays a crucial role in optimizing the design of computer-aided design and computer-aided manufacturing (CAD/CAM) prostheses. It does so by leveraging predictive analysis to thoroughly examine and adjust various factors such

as occlusal forces, contact points, and the overall morphology of dental prosthetics. By harnessing these capabilities, AI reduces the amount of time required for chairside adjustments and fitting, thereby streamlining the workflow in dental practices and enhancing patient satisfaction with quicker, more precise results.[19]

ARTIFICIAL INTELLIGENCE APPLICATIONS IN THE FUNCTIONAL ANALYSIS OF PROSTHODONTICS

Artificial intelligence (AI) is revolutionising the field of prosthetic functional analysis by shifting the approach from traditional subjective evaluationsoften reliant on the clinician's perspectiveto a more objective, data-driven method that emphasises real-time assessment. This transformation is made possible through the integration of advanced technologies, including wearable sensors that continuously monitor various physiological parameters. AI employs machine learning (ML) and deep learning (DL) algorithms to analyse biomechanical data, such as gait patterns, joint angles, and muscle activity. By collecting and interpreting this data, AI systems can provide insights into the user's movement dynamics and overall functionality.[20] This information is instrumental in optimising the design and control of prosthetic devices, thereby enhancing not only their performance but also the overall user experience. For instance, based on real-time data, AI can identify specific areas where a prosthetic may be improved, whether by adjusting the alignment or altering the materials used. Additionally, this cutting-edge analysis enables personalized adaptations to accommodate the unique needs of each user, ultimately leading to improved mobility, comfort, and satisfaction. The incorporation of AI into prosthetic development marks a significant advancement in healthcare, offering the potential to dramatically improve user outcomes and quality of life for those relying on prosthetic limbs.[21]

DISCUSSION

Hamet P et al reviewed in their study that Artificial Intelligence (AI) is transforming prosthodontics by enhancing accuracy and decision-making in dentistry. In implantology, AI uses Convolutional Neural Networks (CNNs) to automate the detection and segmentation of anatomical structures from CBCT scans, reducing manual planning time from about 45 minutes to less than 8, with high accuracy up to 96.4%. AI can also identify and classify dental implant brands from radiographic images with accuracy rates between 71% and 98%.[22,23] Enslin S et al showed in their study that in virtual implant positioning, while robotic systems like Yomi by Neocis provide precise surgical guidance. Predictive analytics assess patient factors to forecast osseointegration success and complications like peri-implantitis. In CAD/CAM design, AI is streamlining the process through generative design techniques, reducing design time and costs while improving quality. AI is advancing modelling capabilities, potentially allowing for 3D models from simple sketches and enhancing additive manufacturing for tailored 3D printing.[24,25] Beyaz S et al included in their study that overall, AI integration is improving accuracy and efficiency in dental technology.Artificial Intelligence (AI) is making significant strides in the field of occlusal and prosthetic analysis, enhancing both diagnostic capabilities and functional outcomes. In occlusal analysis, digital tools leverage AI to analyze virtual articulators, enabling more precise simulations of occlusal contacts and the identification of high points compared to traditional methods. Predictive modelling through machine learning algorithms forecasts future changes in occlusion and simulates the performance of prosthetic restorations, such as removable partial dentures (RPDs).[26,27] Bright TJ et al reviewed in their study that automated design processes allow AI to create the occlusal morphology of crowns and restorations that harmonize with opposing arches, achieving remarkable surface similarity. Additionally, AI models demonstrate high diagnostic accuracy, particularly in recognizing tooth preparation lines and classifying dental occlusion, often surpassing manual assessments in complex cases.[28,29] Aljulayfi IS et al reviewed in their study that the benefits of AI integration in this area include improved efficiency, as it streamlines manual occlusal adjustments and enhances CAD/CAM workflows. AI also plays a vital role in material optimization by helping select materials that better withstand individual patient-specific occlusal loads. However, challenges remain, particularly in terms of data privacy, validation with external datasets, and seamless integration into current clinical practices.[30,31] Revilla-León M et al included in their study that in the realm of prosthetic functional analysis, AI technologies such as Convolutional Neural Networks (CNNs) and Long Short-Term Memory (LSTM) networks analyze data from wearable inertial measurement units (IMUs) to evaluate gait patterns, detect phases of movement, and assess fall risk outside laboratory settings.[32,33] MacrìM et al reviewed in their study that user intent is recognized through analysis of electromyography (EMG) signals, allowing for intuitive control of robotic limbs. Furthermore, AI-driven adaptive control systems can learn unique walking characteristics, adjusting resistance and fluid control in real-time to enhance user comfort and gait symmetry across various terrains.[34,35] Wu Y et al included in their study that AI also aids in prosthetic fitting and optimization by analyzing pressure distribution and sensor data to recommend the best socket fitting and component adjustments, thereby

minimising energy expenditure and tissue damage. Machine learning techniques such as Support Vector Machines (SVM) and Linear Discriminant Analysis (LDA) classify gait events and muscle activation patterns, while deep learning methods like artificial neural networks process complex sensory data for adaptive grip recognition and 3D body orientation modelling.[36,37] Mangano FG et al showed in their study that reinforcement learning techniques further enhance prosthetic adaptability by learning from demonstrations of user movement. Overall, Artificial intelligence has demonstrated remarkable precision, achieving an impressive 95% accuracy rate in recognising user intent. This advancement not only enhances mobility but also significantly lowers the risk of falls, resulting in a more intuitive and seamless experience for users.[38,39] Monalisa S et al reviewed in their study that in the future, innovations are expected to focus on integrating sensorimotor feedback, which will allow for a more responsive interaction with prosthetics. Additionally, the development of IoT-enabled prosthetics will facilitate remote monitoring, enabling healthcare professionals to track user progress in real time. Furthermore, researchers are exploring the potential of brain-computer interfaces (BCI), which could pave the way for prosthetics controlled directly by the user's thoughts, offering an unprecedented level of autonomy and control.[40]

CONCLUSION

In the review "Designing Smarter: AI-Driven CAD/CAM for Immediate Prosthetic Success", the authors explored the beneficial role of AI in prosthodontics. AI-assisted systems are noted for their accuracy, leading to improved marginal adaptation, interproximal contacts, and occlusion in prosthetics. These technologies significantly enhance efficiency by reducing design time and laboratory work, allowing for quicker patient solutions. However, challenges such as the need for more in-vivo clinical trials, data privacy concerns, and high implementation costs hinder broader adoption. Despite these issues, the future of autonomous CAD/CAM workflows looks promising, though human oversight remains essential to ensure safety and validation. Additional comprehensive studies are essential to establish a clearer understanding of the impact and potential of artificial intelligence in the design and development of prosthetic devices.

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