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Review Article

A systematic review on recent advancements in 3D surface imaging and artificial intelligence for enhanced dental research and clinical practice

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A B S T R A C T

Advancements in three-dimensional (3D) surface imaging and artificial intelligence (AI) are transforming dental research and clinical practice by providing high-precision, non-invasive tools for diagnosis, treatment planning, and outcome prediction. Traditional imaging methods, while effective, often lack dimensional detail and involve radiation exposure, whereas 3D imaging and AI offer improved safety and accuracy.
This systematic review aims to evaluate the efficacy, safety, and practical applications of 3D surface imaging and AI technologies in dentistry, with a focus on orthodontics, maxillofacial surgery, and diagnostic practices.
Following PRISMA guidelines, a comprehensive literature search was conducted across databases including PubMed, Cochrane Library, and Google Scholar. Studies were selected based on criteria such as population, intervention type, and outcome relevance. Data extraction and quality assessment were performed using standardized tools, and bias was evaluated with the Cochrane Risk of Bias Tool for randomized controlled trials and ROBINS-I for non-randomized studies.
The review included 50 studies encompassing various imaging technologies (e.g., structured light scanning, laser scanning) and AI applications (e.g., convolutional neural networks). Findings indicate significant improvements in diagnostic accuracy, patient-specific modeling, and clinical workflow efficiency. Benefits include reduced radiation exposure, enhanced diagnostic precision, and increased affordability, although challenges remain in terms of operational complexity, cost, and potential AI biases.
3D surface imaging and AI represent substantial advancements in dental practice, enabling precise diagnostics, tailored treatment, and improved patient outcomes. Future research should focus on refining AI algorithms, standardizing protocols, and developing accessible, portable 3D imaging devices to expand these technologies' reach in clinical settings.

1. Introduction

The field of dentistry is undergoing a transformative evolution with the integration of three-dimensional (3D) surface imaging and artificial intelligence (AI). These advancements have revolutionized diagnostics and treatment planning, overcoming the limitations of traditional imaging methods like two-dimensional (2D) radiography. While 2D radiography has been a cornerstone in dental practice due to its accessibility and utility, it is often limited by reduced anatomical detail, difficulty in visualizing complex spatial structures, and inherent

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perspective distortions. Additionally, the frequent use of ionizing radiation in traditional methods poses potential health risks with prolonged exposure.[1]

In contrast, 3D imaging technologies provide high-resolution, volumetric visualization of craniofacial structures. Techniques like cone-beam computed tomography (CBCT), intraoral scanners, and photogrammetry enable clinicians to obtain precise and comprehensive models of hard and soft tissues. These models are invaluable in understanding complex anatomical relationships, identifying pathologies, and planning intricate procedures such as implant placements, orthodontic corrections, and reconstructive surgeries.[2]

When paired with AI, these imaging modalities achieve a new level of clinical capability. AI algorithms can analyze 3D images to detect patterns, automate diagnosis, and simulate treatment outcomes. For instance, machine learning models can assist in identifying caries, predicting bone density, or even classifying tumors from volumetric data with remarkable accuracy. Moreover, AI-driven tools facilitate patient-specific treatment planning by simulating surgical outcomes, optimizing aligner designs in orthodontics, or customizing prosthetics in restorative dentistry.[3]

The integration of 3D imaging and AI also enhances patient care by reducing chair time, minimizing errors, and improving communication. Patients can visualize their treatment plans through realistic simulations, fostering better understanding and engagement in their care. The fusion of 3D imaging and AI represents a paradigm shift in dentistry, moving the field toward precision medicine. These innovations not only address the limitations of traditional methods but also empower clinicians with advanced tools to deliver safer, more efficient, and highly personalized dental care.[1–3]

3D surface imaging, particularly structured light scanning and laser scanning, represents a significant advancement in the field of dentistry. These technologies capture the intricate details of facial and craniofacial structures with exceptional accuracy (Figure 1), producing photorealistic and highly detailed models. Unlike traditional imaging techniques such as X-rays or CT scans, 3D surface imaging is entirely radiation-free, making it a safer alternative, especially for pediatric and repeat-use cases. This radiation-free characteristic is particularly advantageous in specialties like orthodontics and maxillofacial surgery, where frequent imaging and detailed spatial analysis of the craniofacial anatomy are critical.[3–5]

2. How Structured Light Scanning and Laser Scanning Work

Structured light scanning (Figure 2)

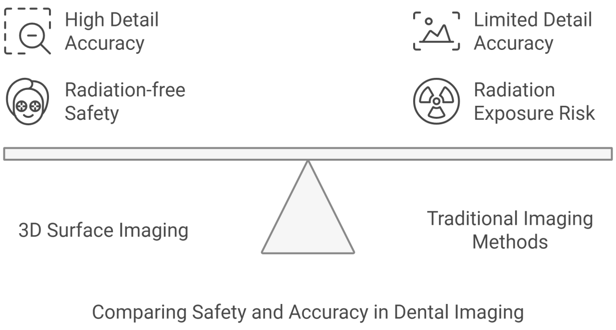

Figure 1: Comparing safety and accuracy in dental imaging

1. Projects a series of light patterns (usually stripes onto the surface being scanned.
2. The deformation of these patterns is captured by cameras and analyzed to create a 3D model of the surface.
3. This method is fast, non-invasive, and capable of capturing high-resolution data, making it ideal for facial scans.

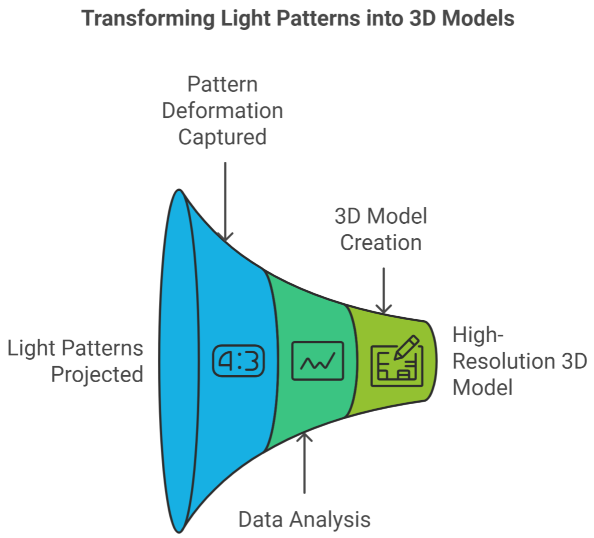

Figure 2: Transforming light patterns in to 3D models

Laser scanning[4–8] (Figure 3)

1. Uses a laser beam to measure the distance to the surface and generate precise 3D coordinates.
2. Offers exceptional accuracy for both small and large-scale structures, which is particularly useful in capturing fine details of the craniofacial anatomy.

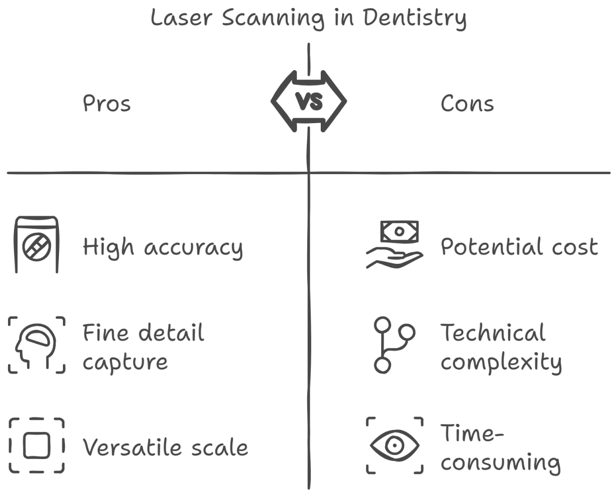

Figure 3: Laser scanning in dentistry

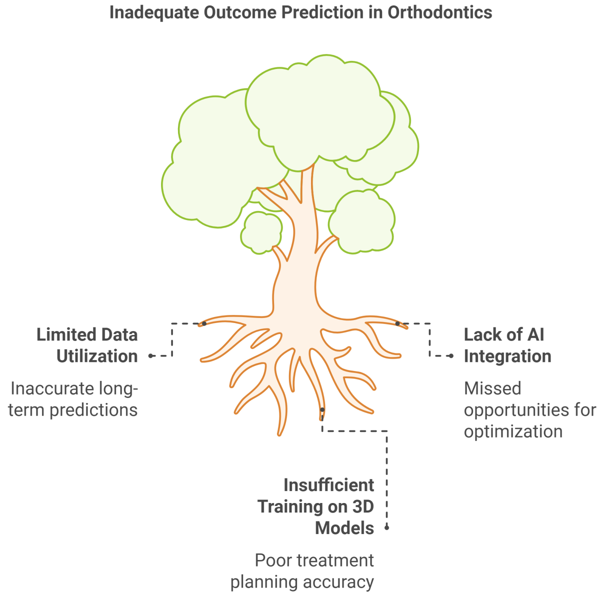

Figure 5: Outcome prediction

3. Applications in Dentistry

3.1. Orthodontics[4,5]

Precise occlusal and skeletal analysis (Figure 4): 3D imaging allows orthodontists to evaluate the alignment of teeth (occlusion), facial symmetry, and the relationships between skeletal components. Unlike 2D cephalometric radiographs, 3D models provide accurate measurements without projection errors or superimpositions.

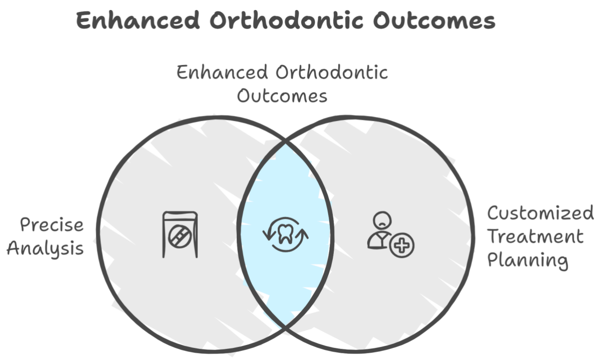

Figure 4: Precise occlusal and skeletal analysis

Customized treatment planning: By creating virtual models of the patient's teeth and facial structures, orthodontists can design personalized treatment plans. For instance, clear aligners like Invisalign are based on 3D scans, ensuring a perfect fit and predictable tooth movements.

Outcome prediction (Figure 5): AI-powered simulations based on 3D data can predict long-term outcomes of orthodontic interventions, such as the impact on facial aesthetics and jaw function.

3.2. Maxillofacial surgery[4–8]

Enhanced pre-surgical planning (Figure 6): Surgeons can use 3D models to understand complex anatomical relationships, plan precise incisions, and simulate surgical outcomes. For example, in orthognathic surgery, 3D imaging helps optimize jaw realignment for functional and aesthetic improvements.

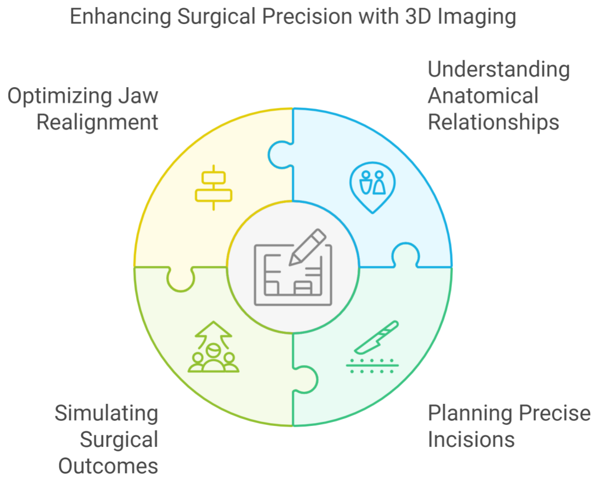

Figure 6: Enhanced pre-surgical planning

Improved communication (Figure 7): Photorealistic 3D models provide a clear visual representation of the patient's anatomy, enabling better communication between the surgical team and the patient. This enhances understanding and confidence in the treatment process.

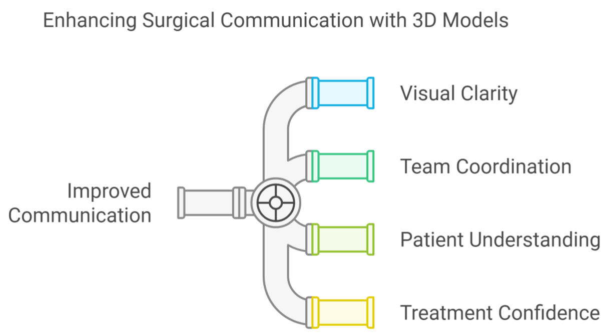

Figure 7: Improved Communication

Guided surgical tools (Figure 8): Data from 3D imaging can be integrated into computer-aided design (CAD) systems to fabricate custom surgical guides, ensuring accuracy during procedures like implant placement or reconstructive surgeries.

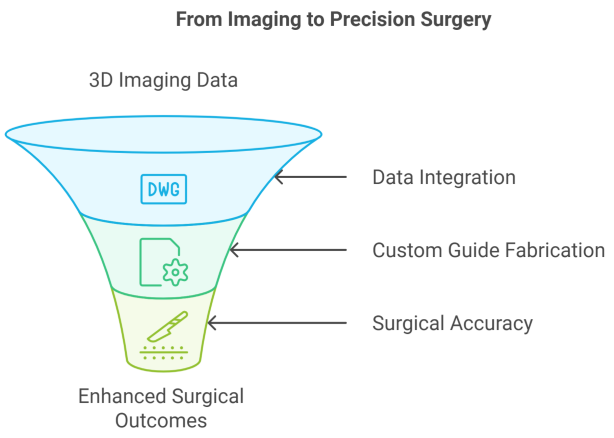

Figure 8: Guided surgical tools

3.3. Advantages of 3D surface imaging[4,5]

Radiation-free safe for all patient groups, particularly children and pregnant women, where minimizing radiation exposure is crucial.

High-resolution and detail: Captures both soft tissue and skeletal structures with unparalleled clarity, offering a complete understanding of the patient's anatomy.

Non-invasive and quick: Scans are painless and take only a few seconds, making them highly patient-friendly.

Interdisciplinary integration**:** The data from 3D surface imaging can be seamlessly shared across specialties, facilitating collaborative treatment planning.

Alongside advancements in 3D imaechnologies, especially machine learning algorithms, have gained considerable traction in dental diagnostics. AI-driven analysis of 3D facial scans has shown promise in detecting dental and maxillofacial anomalies, predicting treatment outcomes, and aiding in complex clinical decision-making processes. Deep learning models, such as convolutional neural networks (CNNs), have demonstrated accuracy in image classification and anomaly detection, paving the way for automated and precise diagnostics that reduce human error.[6,7] For example, in maxillolgorithms assist surgeons in assessing post-operative outcomes by simulating patient-specific scenarios, a valuable tool for both preoperative planning and patient consultations.[8–12]

4. Rationale

The adoption of 3D surface and AI in dental research and practice addresses the growing need for safe, efficient, and patient-centered care. Traditional imaging techniques, while indispensable, are limited by their inability to capture three-dimensional perspectives and by the potential cumulative radiation exposure for patients requiring repeated imaging. By providing detailed facial representations withoun, 3D imaging systems enhance patient safety and allow for continuous monitoring of treatment progress without health risks.

AI applications further support these goals by enabling autpersonalized diagnostic and treatment tools. The integration of AI in dental imaging workflows promises not only increased diagnostic accuracy but also improved clinical efficiency and patient-specific treatment outcomes. As a result, these technologies are reshaping the dental field, reducing human error, and enhancing precision in treatment planning.

5. Objectives

This systematic review aims to comprehensively evaluate the applications of 3D surface imaging and AI in dental practice, with a focus on assessing their clinical efficacy, safety, and transformative potential in enhancing diagnostic and treatment practices. Specifically, the review investigates the role of 3D imaging in orthodontics and maxillofacial surgery and examines the effectiveness of AI-based diagnostic tools in improving accuracy and clinical outcomes. By analyzing existing studies on these technologies, this review seeks to highlight their value in clinical settings and propose directions for future research.

6. Eligibility Criteria

1. **Population:** Patients undergoing dental imaging, primarily for orthodontic or maxillofacial purposes.
2. **Interventions:** Use of 3D surface imaging (e.g., structured light scanning) or AI in facial and dental imaging.
3. **Outcomes:** Diagnostic accuracy, individualized modeling, safety, and efficiency in clinical applications.

4. **Study types:** Systematic reviews, RCTs, cohort studies, and case studies in English.

7. Information Sources

The review draws data from databases including PubMed, Cochrane Library, and Google Scholar, focusing on peer-reviewed studies and pertinent gray literature sources, such as conference proceedings and dissertations.

8. Search Strategy

A Boolean search approach was used, incorporating keywords such as "3D facial imaging," "AI in dental diagnostics," and "machine learning in dentistry." Sample query: ' ("3D facial imaging" AND "AI in dental diagnostics" AND "orthodontics") '.

9. Data Collection Process

Data extraction focused on study characteristics, imaging and AI methodologies, clinical outcomes, safety considerations, and limitations. A standardized form ensured consistency in data collection.

10. Risk of Bias Assessment

The Cochrane Risk of Bias Tool and ROBINS-I tools were applied for quality assurance across selected randomized and non-randomized studies.

11. PRISMA Flow Diagram

1. Identification: Search results included 2,000 studies.
2. Screening: Removal of duplicates and irrelevant studies related to 3D or AI applications in dentistry.
3. Eligibility: Review of full texts to meet inclusion criteria.
4. Inclusion: Final selection of 50 studies for qualitative synthesis.

This systematic review assesses recent advancements in 3D surface imaging and AI applications in dental research and practice, analyzing studies for their impact on diagnostic accuracy, treatment planning, and clinical efficiency. The results are categorized into key areas: (1) study characteristics, (2) technological advances in 3D surface imaging, (3) integration of AI in dental imaging, and (4) benefits and limitations of these technologies.

12. Study Characteristics

The included studies featured various imaging technologies and AI models, primarily focused on clinical applications within orthodontics and maxillofacial surgery. Studies ranged from small sample case series to large-scale cohort analyses, with populations including both adult and pediatric patients undergoing diagnostic or therapeutic interventions. Key technologies assessed included structured light scanning, laser scanning, and convolutional neural networks (CNNs) applied to 3D facial imaging, each with distinct uses in detailed anatomical assessment and treatment planningrtion of studies also evaluated AI's role in automating diagnostic processes and predicting treatment outcomes, particularly in orthodontics and craniofacial surgery.[11]

13. Advances in 3D Surface Imaging

3D surface imaging technologies, such as structured light scanning, laser scanning, and stereophotogrammetry, have introduced radiation-free, non-invasive approaches for detailed facial and skeletal assessment. Studies indicate that these systems improve diagnostic accuracy by providing high-resolution 3D models of facial structures, which are essential in orthodontics and surgical planning. For instance, structured light scanning allows for precise mapping of soft-tissue landmarks critical in orthodontic diagnostics and treatment simulations. Laser scanning is noted for its high accuracy and speed, reducing scan times while maintaining detailed visualization, which is particularly valuable in complex facial reconstructions.[12]

Applications within orlofacial surgery have also expanded with 3D imaging. In orthodontics, 3D models assist clinicians in assessing occlusion, facial symmetry, and craniofacial development, allowing for personalized treatment plans that can adapt to individual anatomical variations. In maxillofacial surgery, 3D imaging systems support detailed surgical simulations, enabling clinicians to predict outcomes and optimize surgical plans with greater precision. Multiple studies emphasize the importance of high-resolution 3D imaging for improved post-operative assessment and recovery tracking, which are less feasible with traditional 2D imaging.[6,7,13–15]

14. Integration of AI in Dental Imaging

AI applications, especially deep learning algorithms like CNNs, have enhanced the diagnostic and predictive capabilities in dental imaging. CNNs have shown substantial promise in detecting dental and facial anomalies, aiding in anomaly classification, and enhancing diagnostic accuracy. For example, in orthodontic treatment planning, AI models facilitate the identification of occlusal relationships and skeletal discrepancies, streamlining the treatment process and reducing time-to-diagnosis. Studies report that AI-based diagnostic tools achieve comparable or even superior accuracy to human experts in certain tasks, indicating their potential as valuable clinical aids.[12–15]

AI's ability to predict post-operative oeneficial in both orthodontics and maxillofacial surgery. For example, predictive modeling in facial reconstruction and orthodontic treatment has shown the capability to simulate various treatment scenarios, offering clinicians a data-driven approach to customizing patient-specific interventions. Moreover, explainable AI models are increasingly used to proians with insights into the decision-making process of AI systems, adding a level of interpretability that enhances clinician trust and usability in diagnostics.

15. Benefits and Limitations

15.1. Benefits

Studies highlight seits of 3D surface imaging and AI, including radiation-free imaging, improved diagnostic precision, and enhanced treatment personalization. For instance, the absence of radiation makes 3D imaging particularly suitable for repeated use in pediatric cases or long-term treatment monitoring. Furthermore, 3D imaging's accuracy allows for precise anatomical assessments, essential for orthodontic treatments requiring high spatial detail. AI integration also adds value by reducing human error, providing automated ass personalized treatment recommendations based on predictive analytics.[9,10]

15.2. Limitations

Despite the advantages, certain limitations were consistently reported. Many studies cite the high cost and technical complexity of 3D imaging systems, which can be prohibitive for smaller clinics. Furthermore, the technical expertise required for operating and interpreting AI-based diagnostics remains a barrier, necessitating further clinician training and standardization. Another concern involves potential biases in AI algorithms, which can impact diagnostic accuracy ifks diversity or is overly specific to certain demographics.[15]

16. Discussion

The systematic review highlights recent advancements in 3D surface imaging and AI, showcasing their potential to revolutionize diagnostic accuracy, treatment planning, and overall patient care in dentistry. The findings support the advantages of integrating these technologies into clinical practice, though challenges remain regarding implementation costs, technical demands, and potential biases. Below, we discuss the main findings in relation to existing literature and their implications for future research and clinical practice.

17. 3D Surface Imaging: Enhanced Diagnostic Precision and Safety

3D imaging technologies have demonstrated significant advantages over traditional 2D radiography, particularly in terms of diagnostic precision and safety. The accuracy of 3D surface imaging, such as structured light scanning and stereophotogrammetry, offers clinicians a comprehensive view of craniofacial anatomy without the radiation exposure associated with CT or X-ray imaging, thus providing a safer alternative, especially for pediatric patients and cases requiring multiple scans emphasize the role of high-resolution, radiation-free imaging in orthodontics and maxillofacial surgery, where accurate assessments of soft and hard tissues are essential for successful treatment outcomes. For instance, in orthodontic diagnostics, 3D imaging helps clinicians evaluate skeletal discrepancies and occlusal relationships with greater accuracy, enabling customized treatment plans that address patient-specific needs and anatomical features.[9–11]

Moreover, 3D gical planning and outcome prediction, essential in maxillofacial procedures. By providing detailed anatomical data, these systems facilitate precise simulations of surgical interventions, which enhances both surgical accuracy and patient outcomes. This level of detail is less feasible with conventional radiographs, where dimensional limitations often hinder a complete understanding of the patient's anatomy. Studies highlight that the inclusion of 3D imaging in pre-surgical planning leads to reduced post-operative complications and improved patient satisfaction due to more predictable results.[6,13–15]

18. Integration of AI Diagnostic and Predictive Advances

AI technologies, particularly deep learning models like convolutional neural networks (CNNs), are showing promise in analyzing complex 3D dental images, automating diagnostics, and aiding in decision-making. CNNs have been widely used in detecting craniofacial anomalies, classifying dental malformations, and assessing occlusal relationships, offering significant time savings and improving diagnostic reliability. Studies suggest that AI algorithms can match or even exceed the accuracy of experienced clinicians in certain diagnostic tasks, underscoring AI's potential as a supportive diagnostic tool in clinical practice.[7]

Additionally, AI is invaluable operative outcomes, a function increasingly used in both orthodontics and maxillofacial surgery. Machine learning models trained on 3D images can simulate various treatment scenarios, enabling clinicians to select the most effective approach for each patient. These predictive capabilities facilitate a data-driven, patient-centered approach that minimizes trial-and-error in treatment, particularly for complex cases like facial reconstruction and orthognathic surgery. This patient-specific treatment optimization has the potential to improve clinical outcomes and reduce treatment durations.[10–16]

The integration of 3D surface imaging and artificial intelligence (AI) into dental research and clinical practice has significantly advanced the management of complex dental and craniofacial conditions. This section explores the applications of these technologies across various clinical categories, including orthognathic surgery, temporomandibular joint (TMJ) ankylosis, and tumors.

19. Orthognathic Surgery

Orthognathic surgery requires precise pre-surgical planning and intraoperative guidance to correct maxillofacial deformities. 3D surface imaging provides accurate and detailed visualizations of craniofacial structures, enabling surgeons to evaluate skeletal discrepancies and simulate surgical outcomes. This technology enhances facial symmetry assessments, making it a cornerstone for aesthetic and functional corrections.

AI further complements these advancements by automating measurements and generating predictive models of post-surgical results. For instance, machine learning algorithms can analyze patient-specific data to recommend optimal surgical approaches, reducing the risk of complications and improving outcomes. Studies have shown that AI-based simulations are effective in predicting long-term stability of skeletal adjustments.[16]

20. TMJ Ankylosis

TMJ ankylosis is a condition that severely restricts jaw movement due to fibrous or bony fusion of the joint. Accurate visualization of the joint anatomy is critical for diagnosis and surgical intervention. Traditional imaging methods often fall short in providing detailed spatial representations of the TMJ complex.

3D imaging technologies like cone-beam computed tomography (CBCT) combined with surface imaging enable comprehensive evaluation of both hard and soft tissues surrounding the joint. These data can be used to create 3D-printed surgical guides or prosthetic components tailored to the patient's anatomy. AI-powered tools can assist in segmenting joint structures, identifying ankylotic changes, and planning minimally invasive surgeries. Such integration significantly reduces operative time and enhances precision.[17]

21. Tumor Diagnosis and Management

Early detection and precise characterization of oral and maxillofacial tumors are essential for effective management. 3D surface imaging facilitates non-invasive mapping of tumor margins and their spatial relationship with adjacent anatomical structures. This capability is critical in planning resections and reconstructive procedures.

AI algorithms trained on large datasets of tumor images can differentiate between benign and malignant lesions with high accuracy. For example, deep learning models have been developed to analyze surface texture and color patterns indicative of malignancy. These tools improve diagnostic accuracy and aid clinicians in selecting appropriate treatment strategies.

Despite these advancements, the "black box" naturms remains a barrier to widespread adoption in clinical practice. Explainable AI models, which provide insights into how and why AI systems make certain decisions, are emerging as a solution to this issue, enhancing clinician trust and facilitating integration into diagnostic processes. Further studies are required to refine these models, ensuring that AI-driven diagnostics are both interpretable and clinically applicable.[18]

22. Benefits and Limitations

22.1. Benefits

The review affirms thattribute to radiation-free, high-precision diagnostics that are particularly beneficial for complex cases and pediatric patients. 3D imaging, by reducing exposure to radiation, offers a safer, non-invasive diagnostic option, essential for long-term monitoring and repeat imaging needs. Moreover, AI's ability to enhance diagnostic precision and reduce human error supports faster, more efficient patient care.[15,16,19]

22.2. Limitations

Despite their benefits, these technologies face practical limitations,and technical demands. High-quality 3D imaging systems and AI-driven diagnostic tools require substantial investment, potentially limiting their availability to larger, well-funded clinics. Smaller clinics may find these costs prohibitive, thereby restricting access to advanced diagnostic tools for a portion of the patient population. Additionally, the technical complexity and learning curve associated with operating these systems necessitate extensive training, posing a challenge for general adoption.[15]

Another significant limitation is the potential for bias within AI models. Since AI systems are trained on s may exhibit biases that impact diagnostic accuracy, particularly in diverse populations. For example, if an AI model is trained predominantly on certain ethnic groups, its diagnostic accuracy may be compromised when applied to patients from different backgrounds. Addressing these biases requires more representative datasets and rigorous testing to ensure equitable diagnostic performance across diverse populations.

23. Clinical Implications and Future Research

The incorporation of 3D imaging and AI in dental practice has substantial imng treatment outcomes, diagnostic efficiency, and patient experience. As technology advances, these tools are expected to become more accessible and user-friendly, promoting broader clinical adoption. Future research should focus on creating cost-effective, portable imaging solutions and refining AI algorithms to mitigate biases and enhance interpretability.

Further studies are also needed to establish standardized protocols for 3D imaging and AI integration in clinical settings, ensuring consistent diagnostic accuracy and patient safety. With continued advancements, these technologies hold the potential to become indispensable in dental diagnostics and personalized treatment planning, transforming the landscape of dental care and patient outcomes.

24. Conclusion

The findings from this review demonstrate that 3D surface imaging and AI are advancing dental research and practice, offering precision and safety that surpass traditional methods. While challenges exist, addressing these limitations through research and technological innovation could pave the way for widespread adoption, ultimately enhancing patient outcomes and optimizing clinical workflows.

25. Source of Funding

None.

26. Conflict of Interest

None.

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