The Bioscan AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES 19(2): S.I (1), 819-826, 2024 www.thebioscan.com

HEALING FACES, RESTORING HOPE: UNLEASHING AI-DRIVEN CLEFT CARE – A NEW ERA IN CRANIOFACIAL SURGERY

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DOI: https://doi.org/10.63001/tbs.2024.v19.i02.S.I(1).pp819-826

KEYWORDS
Artificial Intelligence, Cleft lip and palate, Craniofacial surgery, Multidisciplinary approach, Personalized treatment planning

Received on:

19-09-2024

Accepted on:

27-12-2024

ABSTRACT

Cleft lip and palate are among the most common congenital deformities, affecting millions of children worldwide. These conditions present significant medical, psychological, and social challenges, necessitating complex multidisciplinary treatment involving surgeries, speech therapy, and continuous care. A comprehensive approach to treatment involves a team of specialists, including oral surgeons, orthodontists, and pedodontists, working collaboratively to provide optimal care. Oral surgeons perform the necessary surgical interventions, orthodontists plan the alignment of teeth and jaws, and pedodontists focus on managing the dental needs of young patients. Together, these professionals ensure that the child's growth and development are closely monitored and addressed. In many regions, especially low- and middle-income countries, access to care is limited, leading to further disparities in outcomes. However, the emergence of Artificial Intelligence (AI) is transforming cleft care by enhancing diagnostic accuracy, treatment planning, and surgical precision. AI-driven technologies are enabling more personalized interventions, predicting complications, and improving rehabilitation efforts, thereby enhancing both the clinical and emotional outcomes for patients. This review explores the potential of AI in revolutionizing cleft lip and palate management, focusing on its impact on surgical planning, long-term care, and psychosocial support. By integrating AI into cleft care pathways, healthcare providers can optimize treatment strategies, reduce the burden on families, and ultimately offer hope for a brighter future for children born with orofacial clefts.

INTRODUCTION

Cleft lip and palate represent some of the most prevalent congenital anomalies, affecting an estimated 1 in 600 to 800 live births globally, with over 7.3 million individuals living with orofacial clefts [1]. These conditions, which can occur in isolation or as part of a syndrome, present a spectrum of anatomical, functional, and psychological challenges that extend far beyond the visible physical deformities [2]. The impact of cleft lip and palate is not just in the realm of appearance but spans speech, hearing, nutrition, and oral health, often leading to profound communication difficulties, social isolation, and developmental delays [3]. The prevalence of cleft lip and palate is particularly high in Asian populations, followed by Caucasians and Africans, with males being more affected overall, although isolated cleft palates are more common in females [4]. However, the effects on individuals go beyond the medical realm. Children with cleft lip and palate face heightened risks of speech disorders, orthodontic complications, and developmental delays [5]. Psychosocially, the impact can be devastating—studies reveal that adults with cleft lip and palate experience anxiety, depression, and social challenges at twice the rate of those without the condition. These mental health struggles **[Figure 1]** are exacerbated by the emotional and financial burdens that caregivers bear throughout the prolonged treatment process, which typically involves multiple surgeries, speech therapy, and ongoing medical visits [6]. As such, cleft lip and palate not only imposes physical challenges [**Figure 2**] but also disrupts the lives of families and communities, highlighting the need for holistic, coordinated care.

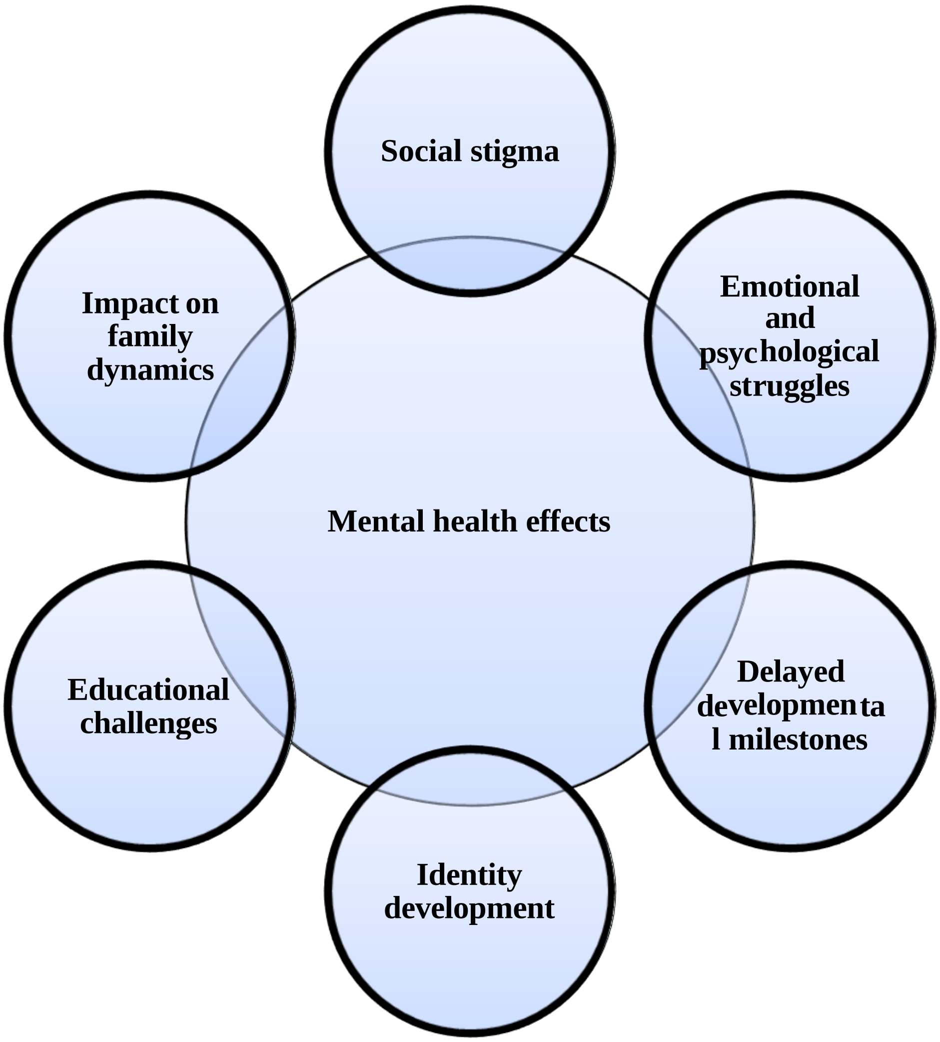

Figure 1: Mental effects of clefting

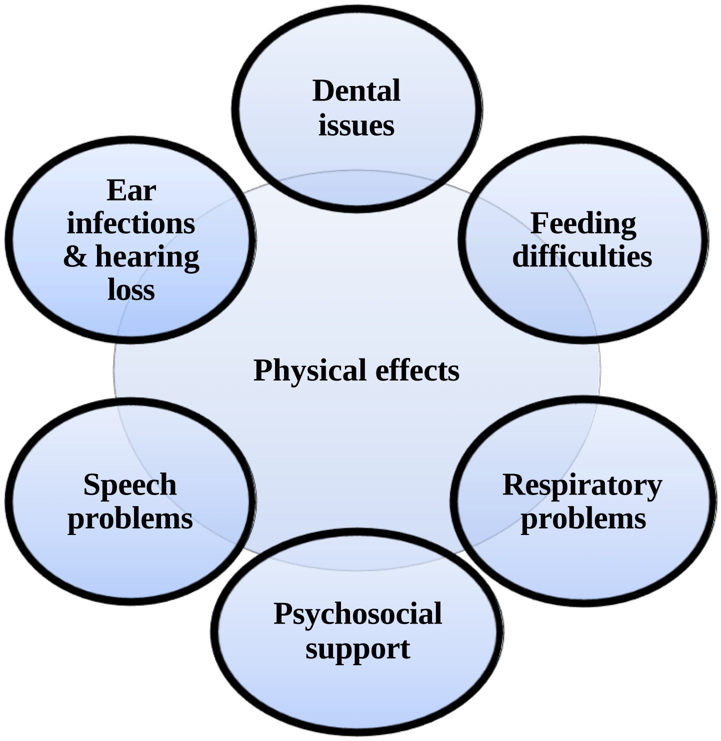

Figure 2: Physical effects of clefting

The traditional approach to managing cleft lip and palate—comprising surgical interventions, speech therapy, psychological support, and frequent medical visits—has provided substantial benefits over the years [7]. The management of cleft lip and palate, a condition affecting millions globally, remains often piecemeal and overwhelming for caregivers, highlighting the need for more streamlined, effective, and compassionate strategies [8]. AI promises to revolutionize cleft lip and palate management by leveraging vast amounts of genetic, environmental, and demographic data to enhance early detection, enable personalized treatment plans, and improve surgical outcomes [9].By identifying genetic variants linked to cleft lip and palate, such as those in Regulatory Factor 6, Msh Homeobox 1, T-box 22, and Bone Morphogenetic Protein 4 (BMP4), AI can predict the risk of cleft lip and palate with unprecedented accuracy [10]. BMP4 plays a crucial role in craniofacial development, as it regulates the formation of the face and palate during embryogenesis. By incorporating BMP4 genetic data alongside environmental factors like maternal smoking or alcohol use, AI can provide a more comprehensive understanding of the complex interactions contributing to cleft lip and palate, leading to more effective preventive strategies and treatments. While the genetic foundations of cleft lip and palate remain complex, advancements in gene interactions, particularly within the WNT gene family and those related to cell adhesion, pave the way for targeted, personalized treatments [11]. Despite challenges such as limited sample sizes and intricate gene-environment interactions, AI's ability to analyze these relationships offers hope for more effective care. As AI evolves, it promises earlier, more accurate diagnoses, better outcomes, and a reduction in the burden on families and healthcare systems worldwide. This convergence of AI, genetics, and personalized care is a paradigm shift in healthcare, offering transformative opportunities for oral surgeons [12].

AI enables the early identification of at-risk patients during prenatal care or shortly after birth, leading to optimized surgical outcomes with personalized pre-surgical planning. Postoperative care is also enhanced, as AI tracks recovery data in real-time, allowing for customized care and early intervention in potential issues like speech or dental problems. Furthermore, AI fosters a collaborative, multidisciplinary approach, ensuring all aspects of a patient's health are addressed, resulting in improved outcomes, better quality of life, and fewer surgeries [13]. As oral surgeons contribute to AI and genetics research, they will shape tools that redefine cleft lip and palate care, empowering them to deliver cutting-edge, individualized care and ultimately transforming the understanding, management, and prevention of cleft lip and palate [14]. This promises not only to improve outcomes for cleft lip and palate patients but also to create a future where cleft lip and palate no longer limits individuals, but instead allows them to lead fulfilling, meaningful lives. This review consolidates AI revolutionizes cleft care, improving early detection, personalized treatment, and outcomes in craniofacial surgery [15].

Research Methodology

In order to examine the ways in which AI may change cleft care, this study takes a descriptive and exploratory research strategy. The study focuses on surgical planning, personalized treatment, and long-term management. In addition, the inquiry makes use of both primary and secondary sources by collecting data. In contrast to primary data, which is collected via expert interviews with craniofacial surgeons, orthodontists, and pedodontists, secondary data is taken from sources like as clinical trials, peer-reviewed publications, and healthcare reports. Using advanced AI algorithms, imaging software, and case studies of specific patients; it is possible to evaluate the accuracy of diagnoses, the efficacy of treatment programs, and the outcomes of surgical treatments. The data is analyzed utilizing statistical tools and machine learning methodologies, which are responsible for the robustness and reliability of the results.

Study Design

In this study, a systematic review approach is used to investigate the application of AI in the treatment of cleft lip and palate. The purpose of this study is to evaluate the advantages, disadvantages, and effectiveness of AI-driven approaches by merging data from past research and clinical trials under different conditions. The primary focus is on significant themes such as the planning for surgical procedures, orthodontic therapy, as well as psychological and social assistance. This comprehensive approach identifies areas where more study is needed and offers a comprehensive understanding of how artificial intelligence might enhance medical outcomes.

Data Sources

A broad range of data sources were used in order to carry out the comprehensive analysis that was required for the research. Researchers make use of scientific databases such as PubMed, Scopus, Web of Science, and Google Scholar in order to locate academic articles and research papers. It is possible to discover information about clinical trials that are now being conducted as well as those that have been completed in databases such as ClinicalTrials.gov and the International Clinical studies Registry of the World Health Organization.

Furthermore, the grey literature includes reports on craniofacial illnesses that have been compiled by non-governmental organizations, conference proceedings, and white papers. Additionally, research that have been published in journals that are focused on artificial intelligence and that are accessible via technological databases such as IEEE Xplore give information on current advancements in the sector.

Inclusion Criteria

1. Research focusing on the use of artificial intelligence in the diagnosis, treatment planning, or surgical implementation of cleft lip and palate.
2. Peer-reviewed academic publications, clinical trials, and systematic reviews.
3. Articles published in English.
4. Research including both paediatric and adult populations with cleft lip and palate.
5. Articles examining interdisciplinary methodologies including orthodontics, oral surgery, and psychological therapy augmented by AI.

Exclusion Criteria

1. Research only examining non-AI therapeutic approaches
2. Case studies or reports with inadequate sample numbers (<10 participants).
3. Articles addressing cleft lip and palate without using AI or technology-based methodologies.
4. Publications in languages other than English.
5. Redundant research or articles without complete text accessibility.

Data Collection

For the purpose of data collection, the following keywords are utilized: "Artificial Intelligence," "Cleft Lip and Palate," "Craniofacial Surgery," "Orthodontics," "Digital Nasolabial Moulding," and "Personalised Treatment Planning." The major emphasis of the study is on publications that span the years 2013-2023, which represents a decade of growth in the field itself. We are able to identify where artificial intelligence is taking care of cleft lip and palate, as well as where new challenges are emerging, by using this approach.

Data Analysis

An in-depth qualitative synthesis of the selected studies may be accomplished via the use of thematic analysis. The research's objectives, methodologies, applications of artificial intelligence, and findings, in addition to other relevant information, are retrieved. There are a number of underlying themes that emerge from the study, some of which include improvements in diagnosis, surgical accuracy, and cost-effectiveness improvements. In order to present a comprehensive picture of the role that AI plays in the treatment of cleft lip and palate, researchers analyze the findings of studies to identify similarities and discrepancies. Within the scope of this research, both achievements and challenges are brought to light, so paving the way for future advances.

PRISMA flowchart of study is shown in **[Figure 3]:**

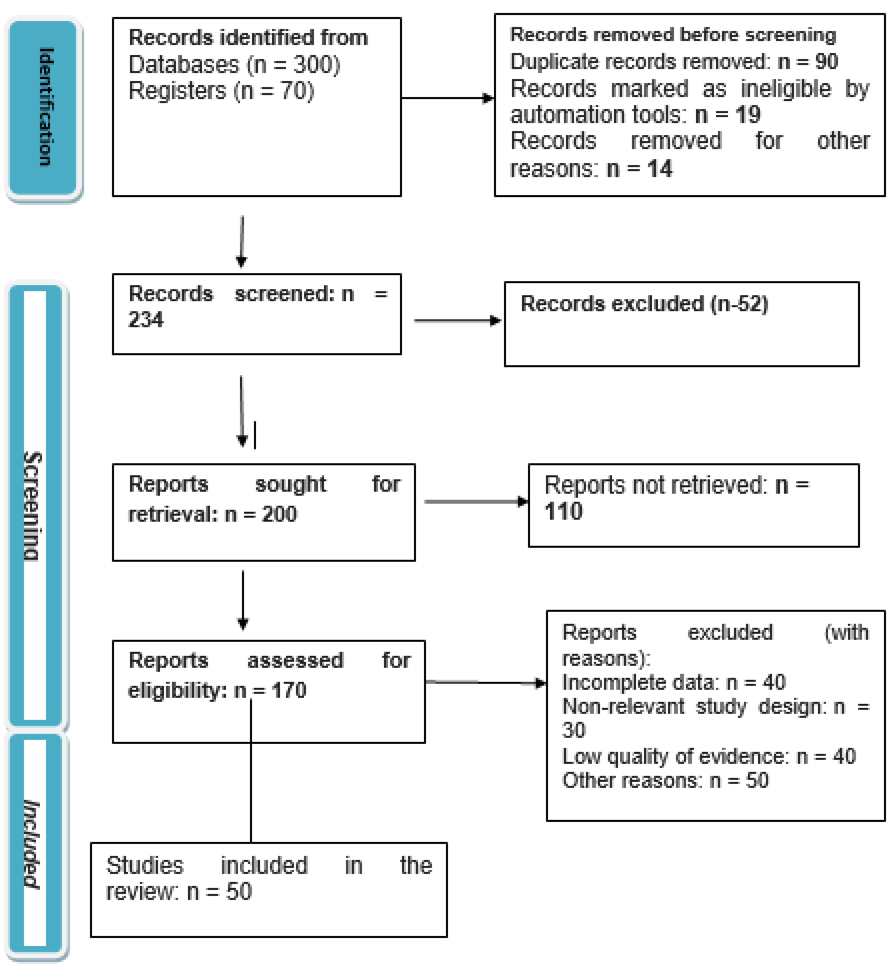

Figure 3: Prisma flowchart

DISCUSSION

Cleft lip and palate are complex congenital conditions that significantly impact an individual's physical appearance, health, and overall quality of life [16]. The deformities range from isolated cleft palates to more severe cases, where there is communication between the nasal and oral cavities. These conditions pose challenges not only to facial aesthetics but also to skeletal development, leading to issues such as maxillary and mandibular retrognathia [17]. Untreated, cleft lip and palate can result in compromised facial growth, hypodontia, and substantial functional limitations, particularly in speech and feeding, as noted by other studies [18]. These conditions have lasting effects that extend beyond childhood, influencing social integration and emotional well-being. The role of orthodontists, oral surgeons, and pedodontists in managing cleft lip and palate is crucial in addressing these multifaceted challenges [19]. Advances in surgical techniques, including innovations like the Afroze incision, which combines elements of the Millard and Pfeifer methods, have significantly improved lip symmetry, nostril alignment, and functional restoration [20]. Oral surgeons play a pivotal role in these procedures, ensuring that both cosmetic and functional aspects of the cleft are addressed during surgery. Orthodontists are key in managing the skeletal and dental development in cleft patients, helping to correct maxillary and mandibular retrognathia and malocclusions [21]. Their expertise is vital in guiding the growth of the teeth and jaws to achieve a harmonious facial appearance and functional alignment. Additionally, AI and digital workflows are transforming how orthodontists, oral surgeons, and pedodontists approach cleft lip and palate care. Early interventions using digital nasoalveolar molding can reduce the need for multiple specialist visits, increase accessibility, and lower infection rates, particularly in underserved areas [22]. AI models, which integrate genetic and environmental data, help predict the risk of cleft lip and palate, enabling early detection and personalized treatment planning. This technology enhances the diagnostic and treatment capabilities of orthodontists and oral surgeons, allowing for more precise and tailored interventions. AI's impact extends to predicting the need for surgeries, orthodontic interventions, and bone grafts, improving overall patient care [23]. For orthodontists, AI-driven tools are especially beneficial in assessing maxillary and mandibular discrepancies, automating complex decision-making processes, and facilitating better treatment planning. These tools assist in predicting the need for extractions, understanding treatment outcomes, and optimizing orthodontic procedures, such as the use of protraction headgear, which is essential in treating craniofacial growth abnormalities in cleft patients. Oral surgeons also benefit from these innovations, as AI can predict the need for orthognathic surgery and bone grafts, enhancing surgical precision and planning. Pedodontists, who care for the dental health of young cleft patients, can leverage AI to optimize treatment for tooth eruption, hypodontia, and other dental anomalies common in these patients [24]. Despite the potential of AI and digital technologies, integrating these tools into clinical practice presents challenges. The development of large, diverse datasets is essential to train AI models effectively, and addressing biases in data is critical. Moreover, real-time feedback and automated monitoring systems are areas requiring further development. Ethical concerns, particularly related to patient privacy, data security, and clinician trust, must be resolved to ensure responsible AI use in healthcare [25]. The future of cleft lip and palate treatment is undeniably tied to the advances in AI, surgical techniques, and digital workflows. These technologies will not only improve the precision and predictability of treatments but also bridge gaps in healthcare access, especially in underserved areas. By embracing these innovations, orthodontists, oral surgeons, and pedodontists can offer more inclusive, effective, and personalized care to those affected by cleft lip and palate, ultimately improving lives and reducing long-term burdens. In conclusion, the integration of advanced surgical techniques, AI-powered diagnostic and treatment models, and a focus on improving healthcare access provides a path forward for cleft lip and palate patients. This multidisciplinary approach is key to achieving better outcomes, fostering better health, and addressing the challenges of cleft lip and palate with the most advanced and accessible solutions available [26]. **[Table 1]** presents an overview of various studies and articles that explore the application of AI and related technologies in cleft lip and palate care.

Table 1: AI and technology in cleft care

Study/ Article Title	Authors	Year	Key Findings	Technology/ Methodology	Relevance to cleft care
3D imaging and AI-based diagnosis in cleft lip and palate repair	Descamps MJ et al. [27]	2010	Discusses AI's potential in diagnosing and planning treatments for cleft lip and palate	3D imaging, AI-based diagnostics	Demonstrates AI's diagnostic capabilities and surgical planning in cleft care
Role of deep learning in cleft lip and palate surgery	Li Y et al.[28]	2019	Examines deep learning algorithms in analyzing patient data and predicting cleft-related issues	Deep learning, neural networks	Details deep learning's ability to predict and assist in cleft surgery decisions
AI-assisted virtual surgical planning for cleft lip reconstruction	Wang Y et al.[29]	2019	Investigates the use of AI-assisted virtual simulations for cleft lip and palate surgery planning	Virtual reality , AI surgical planning	Showcases virtual surgery planning for better outcomes in cleft lip surgeries

AI in pediatric craniofacial surgery: Current trends and future directions	Ryu JY et al. [30]	2021	Reviews trends in AI applications for pediatric craniofacial surgeries, including cleft care	AI-enhanced surgery, robot-assisted surgery, predictive analytics	Covers the evolving landscape of AI in pediatric cleft and craniofacial surgeries
Predictive modeling for cleft lip and palate surgery outcomes	Liu N et al.[31]	2023	AI models predict post-surgical outcomes and complications, improving patient care	Predictive modeling, machine learning	Focus on how AI predicts patient recovery and complications post-surgery
AI in craniofacial surgery: a systematic review	Ravelo V et al. [32]	2024	Explores the use of AI in facial reconstruction and craniofacial deformities treatment	Machine Learning, deep learning, computer Vision	Highlights AI's role in improving surgical precision and treatment planning

Future prospects:

The future of cleft lip and palate treatment is poised to undergo a significant transformation with the continued advancement and integration of AI technologies. AI-driven solutions have already begun enhancing several aspects of medical care, and in the field of craniofacial surgery, AI promises to revolutionize diagnostics, treatment planning, surgical precision, rehabilitation, and long-term patient outcomes [33].

1. **AI-enhanced diagnostics and early detection:** One of the most promising prospects of AI in cleft care is the ability to diagnose and detect clefts earlier and more accurately. Through advanced imaging analysis, AI can identify subtle cleft anomalies even in the earliest stages of pregnancy. Machine learning algorithms, powered by large datasets of medical images, can help clinicians detect cleft lip and palate in prenatal ultrasounds, allowing for earlier interventions and planning, which can significantly improve treatment outcomes. Additionally, AI can assist in differentiating between syndromic and non-syndromic clefts, ensuring personalized care from the outset.
2. **Personalized treatment plans:** As AI continues to evolve, it holds the potential to create highly personalized treatment plans for each patient, tailored to their specific anatomical and genetic profile. AI can integrate data from genetic tests, patient medical history, imaging, and other relevant factors to design individualized care pathways. This could include determining the optimal timing for surgeries, predicting potential complications, and suggesting the best course of action for speech therapy, orthodontics, and psychological support. Personalized medicine powered by AI will ensure that each patient receives the most effective and least invasive treatments, improving both short-term and long-term outcomes [34].
3. **Surgical precision and robotics:** AI is set to play a pivotal role in improving the precision of craniofacial surgeries, particularly in complex cleft lip and palate cases. With the advent of AI-assisted robotic surgery, surgeons can rely on advanced algorithms that provide real-time guidance, ensuring greater accuracy in surgical procedures. AI can analyze 3D imaging to create highly detailed pre-operative models, allowing surgeons to plan and rehearse complex surgeries in a virtual environment before performing them. Robotic systems, powered by AI, can offer enhanced dexterity and consistency, which is especially critical in delicate facial surgeries. This precision can minimize complications, reduce recovery time, and improve aesthetic and functional outcomes.
4. **AI in post-surgical rehabilitation:** After surgery, AI-driven tools can help monitor the patient's recovery progress and provide personalized rehabilitation programs. For instance, AI can track speech development through voice recognition software, allowing clinicians to tailor speech therapy programs more effectively. AI-powered wearable devices can also monitor facial movements, providing real-time feedback on rehabilitation exercises aimed at restoring normal function and aesthetics. This continuous feedback loop will enable healthcare providers to intervene early if there are any deviations from the expected recovery trajectory, leading to faster and more effective healing.
5. **Improved access to care:** In low-resource settings where access to specialized care is limited, AI has the potential to make cleft care more accessible. AI-powered diagnostic tools can be used remotely to assess and monitor patients, offering preliminary consultations or follow-up care via telemedicine. Furthermore, AI-driven platforms could assist local healthcare providers in making informed decisions about treatment options, even in regions with fewer medical professionals. This democratization of healthcare could bridge the gap in cleft care, especially in low- and middle-income countries, where the incidence of clefts is higher and access to expert surgical care may be restricted.
6. **Mental health and emotional well-being support:** AI can also play a key role in addressing the psychological and emotional aspects of cleft care. AI-based mental health support systems, such as chatbots or virtual counselors, can provide immediate psychological support to patients and their families, helping them cope with the emotional burdens associated with cleft lip and palate. AI could also be used to analyze speech patterns and other behavioral cues to identify signs of mental health issues, such as anxiety or depression, in both children and adults. This early identification would allow for timely interventions and personalized mental health care, contributing to better overall well-being [35].

7. **AI-driven research and data analysis:** The integration of AI into clinical and research settings will enable faster and more comprehensive data analysis, driving new discoveries in the field of cleft care. AI can help analyze large volumes of genetic, epidemiological, and clinical data to identify patterns, predict risk factors, and uncover new causes of clefts. This data-driven approach will accelerate research into the genetic and environmental factors that contribute to cleft lip and palate, ultimately leading to more effective prevention strategies and treatments. AI's ability to analyze diverse datasets could also aid in the development of more accurate predictive models for outcomes following surgery or therapy.
8. **Global collaboration and knowledge sharing:** AI can facilitate greater global collaboration by enabling seamless sharing of medical knowledge and best practices across borders. Platforms powered by AI can connect healthcare providers, researchers, and patients worldwide, allowing for the rapid dissemination of new techniques, clinical findings, and treatment outcomes. This exchange of knowledge will promote global standards of care and improve the quality of cleft treatment, especially in underserved regions. Additionally, AI could foster collaboration between different disciplines—genetics, surgery, speech therapy, and psychology—to create more holistic care models for cleft patients [36].

CONCLUSION

The future of cleft lip and palate treatment is filled with exciting possibilities, driven by the power of AI. As AI technologies continue to advance, they will play an increasingly central role in improving diagnosis, personalizing treatment, enhancing surgical outcomes, supporting rehabilitation, and providing psychological care. The integration of AI has the potential to make cleft care more precise, accessible, and effective, ensuring that children and adults with cleft lip and palate have better chances for functional, aesthetic, and emotional recovery. By embracing AI-driven innovations, healthcare providers can restore not only the faces but also the hope of individuals living with this congenital condition, heralding a new era in craniofacial surgery and care.

Financial support and sponsorship Nil

Conflicts of interest There are no conflicts of interest

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