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Review Article

Collaborative Artificial Intelligence Integration in the Management of Cleft Lip and Palate Patients: Current State of the Art

Akadiri Oladimeji Adeniyi[1], Yarhere Kesiena Seun[2]*

[1]Professor, Department of Oral & Maxillofacial Surgery, Faculty of Dentistry, University of Port Harcourt, Rivers State, Nigeria

[2]Doctor, Department of Oral and Maxillofacial Surgery, Faculty of Dentistry, College of Health Sciences. University of Port Harcourt, Rivers State, Nigeria

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***Corresponding author:** Yarhere Kesiena Seun

Doctor, Department of Oral and Maxillofacial Surgery, Faculty of Dentistry, College of Health Sciences. University of Port Harcourt, Rivers State, Nigeria

Abstract

Cleft lip and/or palate (CLP) involves a multidisciplinary and longitudinal care paradigm that provides a rational climate within which collaborative AI systems can buttress clinical decision-making. This study seeks to summarize how Artificial Intelligence AI has been integrated into CLP management by reviewing relevant publications over the past decade while focusing on the deployment of AI into CLP care along the entire care continuum. A pre-existing systematic review analyzing AI in children with CLP was a Foundational Evidence for the study and narratively updated with more recent pediatric craniofacial and orthognathic literature involving CLP subgroups. Other eligible studies had to have leveraged AI or machine learning for CLP-related tasks including diagnosis, landmarking, segmentation, surgical prediction, presurgical orthopedics, or functional outcome evaluation. The results are summarized by clinical domain. Twelve CLP-preferential studies from the prior systematic review, with a number of related craniofacial studies were reported. Across the domains, models tended to record clinically acceptable errors or good classification, reduced clinician's manual workload, and provided standardized (and readily shareable) outcomes for multidisciplinary participation. The majority of publications were retrospective and single-center with small sample sizes and scant external validation. Collaborative AI in CLP care has advanced to early clinical workflows along the care continuum, essentially augmenting clinician's expertise. Equity, ethics, and scalability of implementation will require robust multicenter validation, diverse datasets, governance frameworks, and clinician AI literacy

Keywords: Cleft lip and/or palate (CLP), Artificial Intelligence AI, Machine learning ML, Craniofacial, Cephalometry, Pre-surgical orthopaedics, maxillary segmentation, Orthognathic surgery, speech assessment.

INTRODUCTION

Cleft lip and/or palate is one of the most frequent congenital craniofacial malformations requiring multidisciplinary, longitudinal management from birth to adulthood, with multifaceted decisions related to timing, sequence, surgical intervention, orthodontics, speech therapy, and psychosocial supports (Zambrano *et al*., 2025; Raveendran *et al*., 2023). Traditional treatment paradigms depend on expert-driven interpretation of imaging, manual treatment design, and experience-based prognostication, which are time-consuming and variable (Almoammar, 2024; Huqh, 2022). AI and machine learning (ML) have enhanced automated landmarking, 3D cephalometry, segmentation, virtual treatment simulation, and predictive modeling that enable collaborative decision-making of clinicians with algorithms rather than automation, whereby human expertise or oversight is excluded (Zambrano *et al*., 2025; Raveendran *et al*., 2023; Xu, 2023). This state-of-the art systematic review presents a summary of the literature on the last one decade of efforts toward the integration of AI in CLP care, in terms of current use cases, performance, and translational readiness across the care continuum.

METHODS

Search strategy

The prior systematic review described electronic search processes of PubMed, Scopus, and Web of Science on AI and CLP that identified 44 records and selected 12 studies after screening (Huqh, 2022). The systematic review, the earliest published work found to have discussed how the support of AI tools integrates across the continuum of care in CLP management, involved literature in English language only. In the present synthesis, we took that review as a core Evidence base and updated it narratively with a more recent scoping review (Zambrano *et al*., 2025), as well as other studies in pediatric craniofacial AI, orthognathic surgery, 3D cephalometry, and presurgical orthopedic workflows of CLP subgroups. Search terms included in our review included "cleft lip", "cleft palate", "artificial intelligence", "machine learning", "deep learning", "neural network", "clinical application".

Eligibility criteria

Inclusion criteria in the prior systematic review were: (1) studies on children with cleft lip and/or palate; (2) where AI/ML methods have been used for diagnosis, imaging, treatment prediction or planning, or outcome assessment; (3) clinical or clinical-focused research, not only technical modeling; and (4) complete full-text peer-reviewed articles in English. Exclusion criteria included animal studies, non-AI image processing, editorials, and expert opinions without empirical data. The scoping review used similar selection criteria and gathered 25 articles from 649 initially identified from PubMed, Science Direct, Scopus, and LILACS (Zambrano *et al*., 2025). We followed the same criteria to retrieve other sources including craniofacial AI reviews, specifically CLP-related subanalyses, particularly in orthognathic timing and presurgical plate workflows (Motamedian, 2025; Santos, 2025; Harrison, 2025).

Study selection and data extraction

The systematic review was performed with title/abstract and full-text screening conducted by two independent reviewers with consensus dispute resolution. The extracted key variables of interest included CLP phenotype, task (diagnosis, landmarking, treatment prediction, presurgical or postsurgical evaluation), AI method (e.g. support vector machines, convolutional neural networks, graph convolutional networks, U-Net), dataset size, reference standard, accuracy, sensitivity/specificity, mean error, as well as performance measures. In our present review 15 articles survived the screening criteria out of 23 retrieved from PubMed, Scopus, and Google Scholar databases based on the Mesh terms. For this paper, we cluster the evidence available into conceptual regions along the continuum of CLP care and add narratives about emerging studies included in other craniofacial cohorts which provide a direct reference for CLP patients.

Risk of bias and scope

The earlier systematic review (Huqh, 2022) identified small samples, retrospective analysis and single-center data as leading weaknesses across the CLP AI studies included in the review. The more recent scoping review (Zambrano *et al*., 2025) corroborated these observations. Many of the models were without external validation and were created via heterogeneous imaging protocols. The use of "state-of-the-art" for these findings will be key; thus, this paper is best treated as a synthesis rather than a quantitative meta-analysis; a synthesis that emphasizes translational themes, and collaborative integration into clinical workflows.

RESULTS

Overview of AI applications across the CLP pathway

The 12 CLP-centric studies included in the previous review (Huqh, 2022) grouped into: 1) cephalometric landmark detection and 2D/3D analysis, 2) prediction of demand for later orthognathic operation, and 3) decision support and automated measurements for the planning of treatment. Likewise, a recently published scoping review (Zambrano *et al*., 2025) specifically defined AI integration as the convergence of diagnosis, prediction, treatment, and education in managing CLP. The other related studies for the craniofacial population, CLP in particular, carry these applications to further advanced 3D cephalometry with deep learning, automated maxillary segmentation and cleft filling alongside AI-supported presurgical orthopedic plate design and fabrication (Motamedian, 2025; Santos, 2025; Harrison, 2025; Nalabothu, 2025; Agaronyan, 2025; Almoammar, 2024; Gracea, 2024; de Oliveira, 2024; Jathanna, 2024; Xu, 2023; Zhang X, 2023; Zhang AS, 2023). Table 1: Summary of AI applications across diverse cleft lip and palate management domains

Artificial Intelligence for Cephalometric Landmarking and 3D Cephalometry

To automate 3D cephalometric landmark detection specifically in CLP patients, deep learning models have been applied (Agaronyan, 2025; Xu, 2023). Specifically, a graph convolutional neural network trained on 3D point-cloud data obtained from CLP patients' CT scans produced localized and clinically acceptable detection of cephalometric landmarks within approximately 16 seconds in each dataset when compared to manual reference points (Xu, 2023). Early in a systematic review, the authors conclude that AI-enabled cephalometric analysis can yield quick, reproducible measurements valuable to clinical decision-making and longitudinal growth assessment with children with corrected unilateral CLP (Huqh, 2022).

Prediction of orthognathic surgery need and timing

Cephalometric predictors can predict patients at high risk of orthognathic correction, and individuals who can tolerate orthodontics alone, to enable early risk stratification for families and multidisciplinary teams (de Oliveira, 2024; Jathanna, 2024). To test larger sets of craniofacial cohorts, mixed ML approaches of multiple algorithms exhibited a good predictive accuracy (area under the curve up to about 0.79–0.89) from lateral cephalograms indicating orthognathic surgery indications, demonstrating the potential of AI-informed decision tools applicable for CLP cases involving maxillofacial deformities (Motamedian, 2025; Santos, 2025; Harrison, 2025).

AI has been exploited in the assessment of skeletal maturity in patients with CLP for optimal timeliness of definitive orthognathic surgery by permitting objective, rather than subjective assessment of growth completion prior to major jaw surgery (Harrison, 2025; Huqh, 2022). These models directly enable collaboration by providing quantitative outputs that frame growth stage and treatment timing discussions between surgeons, orthodontists, and families.

Alveolar cleft reconstruction through automated segmentation

The automatic segmentation of the maxilla and cleft section in unilateral CLP patients via AI-based 3D U-Net models was performed with simultaneous “auto-filling” to reconstruct the volume of the alveolar cleft and estimate the effect of bone grafting (Almoammar, 2024; Zhang X, 2023). In a single study, cleft and maxilla segmentation was performed with effective and accurate segmentation using the model, yielding fine-grained cleft-side and non-cleft-side comparisons after secondary alveolar bone grafting, and allowing quantification of the correlation between cleft morphology, preoperative maxillary variance, and post-graft growth patterns (Zhang X, 2023). Combined segmentation and volumetric analyses can facilitate joint and multi-surgical treatment planning estimation of donor-site volume and long-term outcomes auditing, as well as collaboration among surgeons and orthodontists.

AI-assisted presurgical orthopedics and plate therapy

Using a smartphone-based scanning approach, an assortment of mobile 3D scanning applications to produce palatal models were evaluated and an automated machine-learning tool was adopted to automatically analyze morphology and create presurgical plate designs (Santos, 2025). The ML component demonstrated great ability for morphological recognition and automated presurgical plate generation, indicating that low-cost, cloud-based workflows could support centers with limited access to conventional lab-based technologies.

In a retrospective cohort in which a smartphone was used and AI-assisted workflow for preoperative orthopedic therapy in newborns with unilateral CLP was applied, automated plate fabrication was effective and linked to the reduction in anterior cleft width of approximately 56.8% and cleft area of about 40.8% during the presurgical phase as well as the increase of the maxillary segment (Nalabothu, 2025). Further assessment of effectiveness relies on establishing AI-designed passive plate therapy to reduce cleft size before primary surgery, further reducing the need for technical intervention and maximizing access (Benitez, 2024). Collaborative AI is represented with clinician-defined treatment goals supplemented with automated design and manufacturing pipelines.

Prenatal detection and severity classification

In general pediatric craniofacial AI reviews, AI-based prenatal detection and severity classification of cleft lip and palate using ultrasound and other imaging modalities are described; however, the specific CLP-only model details are often embedded within larger datasets (Harrison, 2025). AI algorithms may be used to detect subtle facial anomalies, classify cleft severity, and assess the potential for redirecting cases to craniofacial centers, facilitating early parental counseling and multidisciplinary planning. This results in an integrated upstream collaborative contact for fetal medicine professionals, craniofacial surgeons, and families with an automatic analysis of visuals (Harrison, 2025).

Assessment of speech and functional outcomes

The AI in the pediatric craniofacial area also mentions uses for postoperative speech assessment, in which AI models are trained to process speech recordings, detect hypernasality, and measure articulation errors post CLP repair in children (Harrison, 2025; Zhang AS, 2023). These services can provide standardized evaluation, permit online follow-up, and help speech therapists and surgeons, through objective indices, to follow progress and compare surgical techniques (Harrison, 2025; Zhang AS, 2023). AI-assisted speech analysis, however, is consistent with the multidisciplinary, long-term care for CLPs, despite data limitations.

Table I: Major AI application domains relevant to cleft lip and palate care

Domain	Clinical task in CLP context	Typical AI methods	Collaborative benefits
Cephalometric landmarking	2D/3D measurements, growth analysis	Deep learning, CNNs, graph CNNs	Faster, reproducible measurements for surgeons and orthodontists.
Orthognathic surgery prediction	Early prediction of future jaw surgery need	ML classifiers, ensemble models	Shared prognostic information for families and teams.
Skeletal maturity assessment	Timing of definitive orthognathic surgery	AI-based maturity classifiers	More objective timing decisions in CLP patients.
Maxillary segmentation/cleft fill	Alveolar cleft volume, graft planning	3D U-Net segmentation	Quantitative planning and outcome measurement for grafts.
Presurgical plate design	Presurgical orthopedics for newborns	ML morphology recognition, design automation	Rapid, accessible plate workflows using smartphones and AI.

Domain	Clinical task in CLP context	Typical AI methods	Collaborative benefits
Prenatal detection	Identification and severity grading of fetal CLP	Image classification, DL on ultrasound	Early referral and counseling.
Speech assessment	Postoperative speech quality evaluation	Audio analysis, ML classifiers	Objective monitoring for speech therapy.

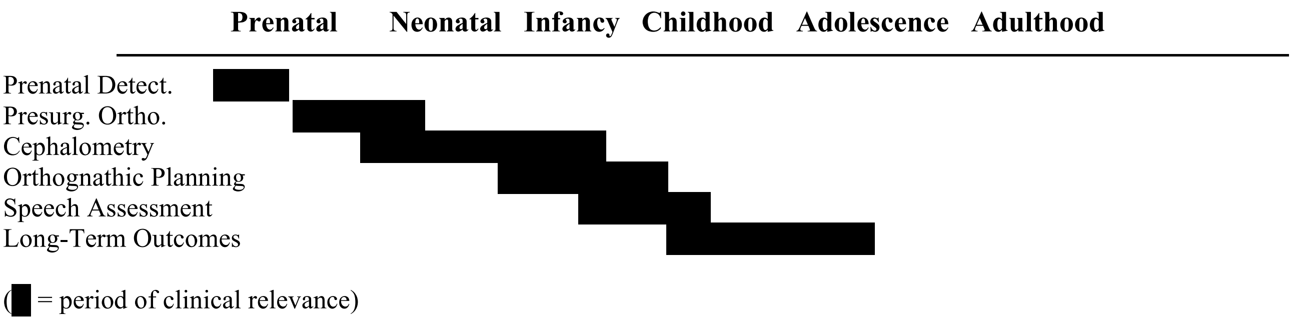

Figure 1: Matrix of Collaborative AI–Clinician Interaction Across Domains of Cleft Lip and Palate Management

Table II. Clinician–Artificial Intelligence Interaction Across the Life-Course of Cleft Care

Prenatal:	Neonatal/Infancy:	Childhood:	Adolescence:	Adulthood:
AI → Clinician (risk detection) Clinician → AI (feedback on false positives)	AI → Orthodontist (NAM planning) Orthodontist → AI (adjustments)	AI → Orthodontist (growth prediction) Orthodontist → AI (manual corrections)	AI → Surgeon (orthognathic simulation) Surgeon → AI (refinement)	AI → SLP (speech scoring) SLP → AI (label corrections) AI → Multidisciplinary team (long-term outcome prediction)

DISCUSSION

Collaborative integration: Across the continuum of care for cleft

Existing AI in CLP management most commonly augment clinicians, as opposed to working as standalone systems, strengthening a shared decision-making system instead of a technology replacement system. For prenatals, AI-assisted imaging tools enable obstetricians and radiologists to pick up on subtle cleft features missed during the normal course of ultrasound, maintaining diagnostic stability and allowing early interdisciplinary interactions (Harrison, 2025). Beyond the standard anomaly detection, new systems can describe laterality, extent, and related anomalies of cleft, allowing more informed counselling and anticipatory guidance for families.

In infancy, AI-assisted presurgical orthopedics extends this collaborative model by combining smartphone-based scanning, automatic segmentation and algorithmic plate design with surgeon-based treatment protocols (Santos, 2025; Nalabothu, 2025). These do not replace clinical judgment so much as they simplify a repetitive process of creating design tasks, minimize reliance on specialized locations of care, and empower the clinician with individualized modifications. In practice, in resource-constrained settings, such hybrid systems may provide some form of decentralised presurgical therapy access with clinician oversight to allow safety and appropriateness considerations even as presurgical care remains in the hands of patient prescribers.

At all stages during growth, AI-based cephalometry and predictive modeling aid orthodontists and surgeons by providing more precise and ongoing assessment for craniofacial development. Automated landmarking minimises the manual workload and inter-observer variability, while growth-prediction models provide estimations of future skeletal relationships, requirements for orthognathic surgery, and anticipated effects of future treatment (de Oliveira, 2024; Jathanna, 2024). In perioperative settings, automated segmentation and 3D reconstruction of maxilla, alveolus, cleft site with 3D model data to visualize the mass field give a solid numerical information for the multidisciplinary team to share that help communication and surgical planning.

At later years, AI-enhanced speech assessment and functional outcome analysis provide scalable instruments for chronic follow-up, especially in settings where trained speech-language pathologists are less available (Almoammar, 2024; Zhang X, 2023). Automation in the scoring of resonance, articulation and intelligibility can help to support early identification of persistent deficits and to direct patients for referral for therapy or second operation procedures. Throughout these stages, these tools focus on teamwork rather than automation, and clinicians validate outputs, correct errors, and incorporate AI-driven insights into holistic care (Harrison, 2025; Zhang AS, 2023).

Performance, validation, and generalizability

AI models reported in the domain show good accuracy and acceptable error margins in clinical, particularly landmark detection, segmentation, binary detection for surgical indications. But evidence is severely constrained by methods, and the evidence base is yet to have the best quality. The majority of the studies are based on retrospective single-center data set and sample sizes are modest, therefore generalization to other CLP phenotypes, ethnicity and imaging protocols is limited (Zambrano et al., 2025; Hugh et al., 2022). Excessive variation in the quality of imaging, scanner type, and annotation standards also hampers a cross-study comparison. External validation—important for evaluating robustness—is little known and no models have been benchmarked using commercial software or multi-expert consensus. In presurgical orthopedic workflows, early clinical cohorts recommend significant reduction of cleft width and area at standard AI-assisted protocols, but such findings are limited (and long-term effects on surgical complexity, facial growth and functional outcomes are not adequately confirmed) (Hugh, 2022). These new data are not of sufficient size, prospective, or geographically diverse enough to have the potential to provide reliable transfer of current performance metrics into real-life clinical situations.

Ethical, practical, and equity considerations

AI as part of CLP care presents important ethical and practical concerns. Privacy and informed consent are of paramount importance when cloud-based facilities or data transference between borders play a role. Algorithmic bias is another danger, as the AI systems trained on homogenous datasets may perform poorly in populations with different craniofacial morphologies, imaging or linguistic distributions. This is particularly relevant due to the fact that many CLP patients reside in low- and middle-income settings where digital infrastructure, high-resolution imaging, and computational resources may be challenged.

Nevertheless, smartphone-based scanning technology, inexpensive 3D photography methods, and cloud-hosted AI workflows provide hopeful pathways for scalable and equitable deployment—including addressing governance, connectivity, and data-security issues. Collaborative integration, from a clinical perspective, demands explicit workflow design: defining human versus AI responsibilities, providing training for clinicians on ways to interpret and challenge algorithmic outputs, and providing mechanisms to override AI recommendations if those recommendations conflict with clinical decision-making. Lacking such protections, such a reliance on automatic outputs can threaten the practitioner autonomy.

Future directions

Further research should be focused on multicenter, prospective studies of the effect of AI tools integrated into typical CLP pathways with clinically meaningful endpoints of diagnostic accuracy, surgical impact, speech function, patient-reported quality of life, and cost-effectiveness in AI testing (Zambrano et al., 2025; Hugh et al., 2022). Open, well-annotated CLP imaging data sets on prenatal ultrasound, CT/CBCT, 3D photography and speech audio are urgently needed to enable reproducible benchmarking and external validation of CLP AI techniques.

Additionally, digital twin integration—comprehensive biomechanical and data-driven models of individual patients—can also be utilized to augment personalized planning for lip repair, palatoplasty, alveolar bone grafting, and orthognathic surgery. These models may model growth trajectories, predict surgical outcomes, and optimize intervention timing. Ultimately, the use of AI will require capacity-building across the whole cleft care continuum through AI literacy training for surgeons, orthodontists, speech therapists and allied professionals. The schematic (Fig. 1) takes a holistic look at how artificial intelligence can aide clinical decision-making in the entire continuum of cleft lip and palate care. The alignment of the large life-stage milestones — prenatal, neonatal, infancy, childhood, adolescence and adulthood — with the corresponding domains of AI application illustrates the longitudinal and multidisciplinary nature of cleft management by linking these milestones to the relevant domains of AI application.

Schematic of Collaborative interaction between AI and Clinician for efficient CLP Care

To support the findings presented in this study, we propose a holistic assessment of AI-defined applications in clinical settings for cleft lip and palate care. As demonstrated in the matrix, each AI domain fits during the clinical time that it is useful, spanning from prenatal detection to prediction of long-term outcomes.

The other interaction pathways highlight that AI is not positioned as a self-determining decider but as a collaborative enterprise: the clinician interprets, improves, and provides feedback on AI outputs at each stage of development. For example, prenatal risk assessments are reviewed and rectified by clinicians, presurgical orthopedic planning is iteratively updated by AI and orthodontists, and orthognathic simulations are updated with input from surgeons. As a result, communication can be streamlined and efficiency enhanced in the management of cleft lip and palate. Similarly, speech-language pathologists and multidisciplinary teams provide corrections and appropriate contextual judgment in advanced stages.

CONCLUSION

Overall, the illustration communicates a dynamic, two-way alliance, in which AI enhances a clinician's expertise and yet is integrated into existing workflows and professional oversight efforts. The schematic that accompanies this picture highlights this trajectory by positioning AI strengths on the established life-course pathway of CLP care, proposing a conceptual algorithm clinicians can use to gauge when AI tools align with the prior decision points and multidisciplinary interactions. By representing this concept, the illustration reminds us that AI should not be understood as a system in isolation, but as an entwined partner in every stage of care, and the importance of strong, equitable, and ethically sound deployment that frames AI as a complementary pillar to the CLP team. Future initiatives would need to focus on transparent governance, robust assessment of patient-centered outcomes, and ongoing collaboration among clinicians, engineers, and patients to ensure AI complements — as opposed to disrupts — the provision and care trajectory of lifelong cleft care.

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