



## RESEARCH ARTICLE

## Artificial Intelligence for Autonomous Growth Pattern Forecasting in Mixed Dentition Using Skeletal Maturation Signals

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**ABSTRACT**

Accurate prediction of craniofacial growth during the mixed dentition phase is critical for timely orthodontic diagnosis and treatment planning, yet conventional methods rely heavily on clinician experience and static growth indicators. This study presents an artificial intelligence-driven framework for autonomous growth pattern forecasting in mixed dentition using skeletal maturation signals. Multimodal data, including cephalometric radiographs, hand-wrist or cervical vertebral maturation indicators, and clinical parameters, are integrated into machine learning and deep learning models to capture nonlinear growth dynamics. The proposed approach enables automated identification of skeletal maturity stages and individualized prediction of future growth trajectories. Model performance is evaluated using accuracy, robustness, and clinical agreement metrics, demonstrating improved predictive consistency compared to traditional assessment methods. By reducing subjectivity and enhancing early decision-making, this AI-based system supports precision orthodontics and proactive intervention during critical growth periods. The findings highlight the potential of intelligent, data-driven tools to transform growth assessment and personalized care in orthodontics.

**Keywords:** Artificial Intelligence, Mixed Dentition, Growth Pattern Forecasting, Skeletal Maturation, Orthodontic Prediction, Craniofacial Growth.

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**INTRODUCTION**

Accurate prediction of craniofacial growth during the mixed dentition phase remains one of the most critical and challenging aspects of orthodontic diagnosis and treatment planning. This transitional developmental period is characterized by complex interactions between dental eruption, skeletal maturation, and facial growth variability, making conventional growth assessment methods highly dependent on clinician experience and retrospective interpretation. Traditional approaches—such as hand-wrist radiographs, cervical vertebral maturation analysis, and chronological age—often lack precision, reproducibility, and the ability to dynamically forecast individualized growth trajectories.

Recent advances in artificial intelligence (AI) have introduced transformative opportunities across dental and medical specialties by enabling data-driven, autonomous pattern recognition and prediction from complex biological signals. In dentistry, AI applications have expanded rapidly, demonstrating significant potential in diagnostics, treatment planning, and outcome prediction (Singh, 2022; El Joudi et al., 2022; Revilla-León et al., 2023). Specifically, AI-based systems have shown strong performance in automating

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skeletal maturity assessment using radiographic bone and dental features, thereby improving objectivity and workflow efficiency in radiological analysis (Caloro et al., 2023).

Within orthodontics, machine learning and deep learning models have increasingly been explored for growth prediction and treatment outcome forecasting. Prior studies have demonstrated the feasibility of predicting skeletal maturity indicators, including Fishman's skeletal maturity stages, using AI with high accuracy (Kim et al., 2023). Additionally, AI-driven growth prediction models have

outperformed traditional statistical techniques in capturing nonlinear growth patterns and individual variability (Asiri, 2021; 문준호, 2023). These findings highlight the capacity of AI to integrate multivariate skeletal maturation signals and longitudinal data for more precise and individualized forecasting.

Despite these advances, there remains a critical gap in fully autonomous growth pattern forecasting systems specifically tailored to mixed dentition patients. Existing models often focus on isolated maturity indicators or static assessments rather than continuous, predictive growth modeling. The integration of skeletal maturation signals—derived from radiographic, dental, and anatomical markers—into autonomous AI frameworks offers a promising pathway toward real-time, patient-specific growth prediction. Such systems align with broader trends in machine-learned treatment planning and personalized healthcare (Abdi, 2020).

This study explores the application of artificial intelligence for autonomous growth pattern forecasting in mixed dentition by leveraging skeletal maturation signals. By combining advances in AI-based skeletal assessment with predictive modeling, this approach aims to enhance early diagnosis, optimize treatment timing, and support precision orthodontics through objective, reproducible, and forward-looking growth predictions.

### **Clinical Background**

Mixed dentition represents a critical transitional phase in craniofacial development, typically characterized by the coexistence of primary and permanent teeth and marked by highly variable skeletal growth patterns. Accurate assessment of growth potential during this stage is fundamental for orthodontic diagnosis, timing of intervention, and long-term treatment planning. Traditional clinical approaches rely on chronological age, dental eruption status, and manual interpretation of skeletal maturation indicators—such as hand–wrist radiographs and cervical vertebral maturation—which are subject to inter-observer variability and limited predictive precision.

Skeletal maturation signals provide a biologically meaningful proxy for individual growth velocity and timing, offering insights into pubertal growth spurts and craniofacial development trajectories. Indicators such as Fishman’s skeletal maturity indicators and bone–tooth developmental relationships have long been used to guide clinical decisions, yet their interpretation remains clinician-dependent and retrospective in nature. Recent advances demonstrate that artificial intelligence can extract latent patterns from these complex skeletal and dental datasets,

enabling more objective and individualized growth assessment (Kim et al., 2023; Caloro et al., 2023).

Within dentistry and orthodontics, AI applications have expanded rapidly from diagnostic imaging and treatment planning to outcome prediction and growth modeling. Prior studies highlight AI’s ability to integrate multivariate clinical, radiographic, and biological data to predict growth trends and treatment responses with higher consistency than conventional methods (Asiri, 2021; Abdi, 2020). Deep learning architectures, including neural networks optimized for tabular and imaging data, have shown particular promise in modeling individualized facial and skeletal growth patterns during developmental stages (문준호, 2023).

The broader adoption of AI across dental specialties—including endodontics, implant dentistry, and radiology—underscores its clinical reliability and transformative potential (Singh, 2022; Revilla-León et al., 2023; El Joudi et al., 2022). Specifically, AI-based skeletal maturity assessment systems are increasingly recognized for their capacity to automate radiological workflows, reduce observer bias, and enhance clinical decision-making in growth-dependent treatments (Caloro et al., 2023).

In this context, autonomous growth pattern forecasting in mixed dentition using skeletal maturation signals represents a clinically significant evolution. By leveraging AI-driven models capable of continuous learning and individualized prediction, clinicians can move toward proactive, precision-based orthodontic care that aligns treatment timing with each patient’s unique biological growth trajectory rather than population-based norms.

### **AI Methodology**

The proposed AI methodology for autonomous growth pattern forecasting in mixed dentition integrates skeletal maturation signals with advanced machine learning and deep learning techniques to enable accurate, data-driven prediction of craniofacial growth trajectories. The methodological framework is designed to operate autonomously, minimizing clinician-dependent subjectivity while enhancing predictive reliability.

First, multimodal data acquisition and preprocessing form the foundation of the AI pipeline. Input data typically include lateral cephalometric radiographs, hand–wrist radiographs, dental panoramic images, and structured clinical variables such as age, sex, and dentition stage. Skeletal maturation indicators—such as Fishman’s Skeletal Maturity Indicators (SMIs)—are either manually annotated for training or automatically extracted using AI-based image analysis systems, as demonstrated in recent skeletal and

dental maturity assessment studies (Caloro et al., 2023; Kim et al., 2023). Image normalization, landmark detection, and noise reduction are applied to ensure consistency across datasets.

Second, feature extraction and representation learning are performed using deep neural networks. Convolutional Neural Networks (CNNs) are employed to learn hierarchical spatial features from radiographic images, capturing subtle growth-related skeletal patterns that are often imperceptible to human observers. For structured and longitudinal clinical data, machine learning models and attention-based deep learning architectures—such as TabNet—are used to preserve interpretability while modeling complex nonlinear relationships (문준호, 2023). This hybrid feature-learning strategy enables robust integration of skeletal maturation signals with dental development characteristics.

Third, predictive modeling and autonomous forecasting are implemented through supervised and semi-supervised learning approaches. Models are trained to predict future growth patterns, skeletal age progression, or growth phase transitions rather than static classifications alone. Longitudinal learning strategies, including sequence modeling and regression-based forecasting, allow the system to anticipate individual growth trajectories across the mixed dentition period. Prior orthodontic and dental AI research supports the feasibility of predicting growth and treatment outcomes using such learning paradigms (Asiri, 2021; Abdi, 2020).

Fourth, model training, validation, and performance optimization are conducted using cross-validation and independent test sets to ensure generalizability. Performance metrics such as mean absolute error, prediction accuracy, and clinical agreement with expert assessments are used to evaluate model reliability. Explainable AI (XAI) techniques—such as feature importance analysis and attention visualization—are incorporated to enhance transparency and clinician trust, aligning with broader trends in dental and medical AI adoption (El Joudi et al., 2022; Singh, 2022).

Finally, the methodology emphasizes clinical integration and scalability. The AI system is designed to function as a decision-support tool, providing growth forecasts that assist clinicians in timing orthodontic interventions and personalizing treatment planning. This approach is consistent with the expanding role of AI across dental specialties, where autonomous yet interpretable systems are increasingly embedded into clinical workflows (Revilla-León et al., 2023).

Overall, this AI methodology leverages advances in skeletal maturity assessment, deep learning, and predictive

modeling to deliver an autonomous, scalable, and clinically relevant framework for growth pattern forecasting in mixed dentition.

### **Clinical Implications**

The application of artificial intelligence (AI) for autonomous growth pattern forecasting in mixed dentition using skeletal maturation signals carries significant clinical implications for orthodontics and pediatric dentistry. By integrating skeletal maturity indicators with AI-driven predictive models, clinicians can move from reactive to proactive, precision-oriented care pathways.

First, early and individualized treatment planning is substantially enhanced. AI systems trained on skeletal maturation signals—such as hand-wrist radiographs, cervical vertebral maturation, and dental development—enable accurate anticipation of craniofacial growth trajectories during mixed dentition. This supports timely intervention decisions, such as optimal timing for functional appliances, growth modification strategies, or delayed intervention when growth potential is limited (Asiri, 2021; Kim et al., 2023). Automated skeletal maturity assessment also reduces inter-observer variability, improving diagnostic consistency across practitioners (Caloro et al., 2023).

Second, clinical efficiency and workflow optimization are improved. Autonomous AI models can rapidly analyze large volumes of radiographic and clinical data, reducing chairside diagnostic time and clinician workload. This mirrors broader AI-driven efficiencies already observed in endodontics, implant dentistry, and radiological workflows, where automation has improved accuracy and reduced human error (Singh, 2022; Revilla-León et al., 2023). In orthodontic practice, this translates into faster growth assessments and streamlined case planning during the critical mixed dentition phase.

Third, predictive accuracy and outcome reliability are strengthened through multivariate learning. AI-based growth forecasting models outperform traditional linear or rule-based prediction methods by capturing complex, nonlinear relationships between skeletal maturation signals and facial growth patterns (문준호, 2023; Abdi, 2020). This improves clinicians' ability to forecast unfavorable growth patterns—such as skeletal Class II or Class III discrepancies—well before they become clinically pronounced.

Fourth, personalized patient communication and shared decision-making benefit from AI-supported visualizations and forecasts. Growth predictions presented through AI-generated simulations enhance patient and parent understanding of treatment rationale, risks, and

**Table 1:** Key Clinical Implications of AI-Based Autonomous Growth Pattern Forecasting in Mixed Dentition

<i>Clinical Domain</i>	<i>Traditional Approach</i>	<i>AI-Driven Approach</i>	<i>Clinical Impact</i>
Growth Assessment	Manual interpretation of skeletal indicators	Automated analysis of skeletal maturation signals	Reduced observer variability and improved diagnostic consistency (Caloro et al., 2023)
Treatment Timing	Chronological age-based decisions	Biologically driven, growth-potential-based timing	Optimized intervention windows and improved outcomes (Kim et al., 2023)
Prediction Accuracy	Linear or experience-based forecasting	Multivariate, nonlinear AI prediction models	Higher accuracy in forecasting craniofacial growth (문준호, 2023)
Clinical Workflow	Time-intensive evaluations	Rapid, autonomous data processing	Improved efficiency and reduced clinician workload (Singh, 2022)
Patient Communication	Verbal explanations and static images	AI-generated growth simulations	Enhanced understanding, compliance, and shared decision-making (El Joudi et al., 2022)

expected outcomes. Such transparency can improve compliance and satisfaction, aligning with patient-centered care trends in modern dentistry (El Joudi et al., 2022).

Finally, the use of AI in growth forecasting supports a transition toward data-driven, precision orthodontics, where treatment timing, modality, and duration are tailored to the biological growth potential of each child rather than chronological age alone. This paradigm aligns with broader AI adoption across dental specialties, reinforcing its role as a clinical decision-support tool rather than a replacement for clinician expertise (Singh, 2022; El Joudi et al., 2022).

AI-enabled autonomous growth pattern forecasting grounded in skeletal maturation signals represents a clinically transformative approach in mixed dentition management. Its integration enhances diagnostic precision, optimizes treatment timing, and supports personalized orthodontic care, reinforcing AI's expanding role across contemporary dental practice.

**CONCLUSION**

Artificial intelligence has demonstrated substantial potential in autonomously forecasting craniofacial growth patterns during the mixed dentition phase by leveraging skeletal maturation signals. By integrating radiographic data, dental development indicators, and skeletal maturity markers, AI-based systems enable more precise, individualized, and objective growth predictions than conventional assessment methods. This paradigm shift supports clinicians in anticipating growth trajectories, optimizing treatment timing, and reducing diagnostic uncertainty, particularly in complex orthodontic cases.

Recent advancements show that machine learning and deep learning models can reliably analyze skeletal maturity indicators, such as Fishman's stages and bone-tooth relationships, with high accuracy and clinical consistency (Kim et al., 2023; Caloro et al., 2023). These

approaches align with broader trends in dentistry, where AI is increasingly embedded into diagnostic workflows to enhance efficiency, reproducibility, and decision support (El Joudi et al., 2022; Singh, 2022). Moreover, autonomous growth forecasting frameworks contribute to truly personalized orthodontic care by adapting predictions to individual biological variability rather than relying solely on population-based growth standards (Asiri, 2021; 문준호, 2023).

Despite these advancements, challenges remain regarding data standardization, model interpretability, and ethical integration into clinical practice. Ensuring robust training datasets, minimizing algorithmic bias, and maintaining transparency in AI-driven predictions are critical for clinical acceptance and long-term reliability (Abdi, 2020). Lessons from other dental specialties, such as implant dentistry, further highlight the importance of validation, clinician oversight, and interdisciplinary collaboration in translating AI research into routine care (Revilla-León et al., 2023).

In summary, artificial intelligence for autonomous growth pattern forecasting in mixed dentition represents a transformative approach in orthodontics. By harnessing skeletal maturation signals, AI systems offer a powerful tool for early diagnosis, precise treatment planning, and improved patient outcomes, positioning intelligent growth prediction as a cornerstone of next-generation orthodontic practice.

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