Research Article

Neuro-Adaptive AI Systems for Predicting Root Resorption Susceptibility During Orthodontic Tooth Movement

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External root resorption remains one of the most significant iatrogenic risks associated with orthodontic tooth movement, often progressing asymptomatically until irreversible damage occurs. This study proposes a Neuro-Adaptive Artificial Intelligence (AI) system for predicting individual susceptibility to root resorption by dynamically integrating multimodal clinical, imaging, and biomechanical data. The proposed framework leverages brain-inspired adaptive learning models capable of continuously updating risk predictions in response to patient-specific biological responses and treatment progression. High-resolution CBCT-derived root morphology, orthodontic force vectors, treatment duration, patient demographics, and genetic and inflammatory biomarkers are incorporated to enable personalized risk profiling. By transitioning from static risk assessment to real-time, neuro-adaptive prediction, the system aims to support clinicians in optimizing force application, minimizing adverse outcomes, and enhancing treatment safety. The proposed approach aligns with emerging trends in precision orthodontics and AI-driven clinical decision support systems, offering a scalable pathway for early detection and prevention of root resorption in contemporary orthodontic practice.

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Introduction & Clinical Significance

Orthodontically induced root resorption (OIRR) remains one of the most clinically significant and unpredictable adverse outcomes of orthodontic tooth movement. Despite advances in biomechanics, imaging, and treatment planning, the biological response of dental and periodontal tissues to orthodontic forces varies substantially across individuals, making early identification of high-risk patients challenging. Root resorption is often asymptomatic and irreversible, with severe cases compromising tooth longevity and overall treatment success. Consequently, there is a growing clinical demand for intelligent systems capable of predicting individual susceptibility before and during treatment, enabling proactive risk mitigation rather than retrospective management.

Artificial intelligence (AI) has demonstrated increasing relevance in dental and orthodontic domains, particularly in pattern recognition, imaging analysis, and decision support. Prior AI applications in dentistry have largely relied on static models trained on retrospective datasets, limiting their ability to account for dynamic biological adaptation over time (Singh, 2022). However, orthodontic tooth movement is inherently a time-dependent, non-linear biological process influenced by force magnitude, duration, tissue remodeling, and patient-specific factors. This complexity necessitates adaptive intelligence systems that can continuously learn and recalibrate predictions as new clinical data emerge.

Neuro-adaptive AI systems, inspired by neural plasticity and adaptive control theories, offer a promising paradigm for addressing this challenge. Such systems integrate recurrence, feedback loops, and real-time learning to adjust model behavior in response to evolving conditions (Bout, 2023). Neuro-adaptive learning has been successfully applied in complex, dynamic environments including energy systems, reservoir performance prediction, and autonomous control, demonstrating robustness under uncertainty and non-stationary data conditions (Ali & Guo, 2019; Birari, 2017). More recent work highlights the effectiveness of neuro-adaptive architectures in human-centered and safety-critical applications, where continuous adaptation to physiological, cognitive, or environmental signals is essential (Ghulaxe, 2024; Baxi et al., 2024).

Within healthcare and built environments, neuro-adaptive intelligence has been shown to enhance

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system responsiveness to human states and biological feedback, reinforcing its suitability for personalized clinical applications (Makanadar, 2024). Translating these principles to orthodontics enables the development of predictive systems that not only assess baseline risk of root resorption but also dynamically update susceptibility estimates as treatment progresses. By integrating longitudinal imaging data, biomechanical parameters, and patient-specific biological responses, neuro-adaptive AI systems can support clinicians in modulating orthodontic forces, adjusting treatment strategies, and minimizing irreversible tissue damage.

The clinical significance of neuro-adaptive AI in predicting root resorption susceptibility lies in its potential to shift orthodontic care toward precision-driven, biologically informed decision-making. Rather than relying on population averages or delayed radiographic findings, clinicians can leverage adaptive intelligence to anticipate adverse outcomes, personalize interventions, and enhance patient safety. This approach aligns with the broader evolution of intelligent, learning-based healthcare systems that prioritize continuous adaptation, risk prevention, and individualized treatment optimization (Bout, 2023; Singh, 2022).

Data Sources & Biomarkers

Accurate prediction of root resorption susceptibility during orthodontic tooth movement relies on integrating multiple patient-specific data sources. Neuro-adaptive AI systems can dynamically learn from heterogeneous inputs, including imaging, clinical, genetic, and biomechanical biomarkers, to generate real-time risk profiles. Such integration allows AI models to adapt to individual variations in tooth movement response, reflecting the patient-specific nature of root resorption (Singh, 2022; Bout, 2023).

Imaging Biomarkers

Cone-beam computed tomography (CBCT) provides high-resolution 3D imaging, enabling detailed assessment of root morphology, alveolar bone density, and pre-existing resorption defects. Neuro-adaptive models leverage these volumetric features for early detection of risk zones (Singh, 2022). Advanced segmentation and feature extraction methods allow AI to quantify subtle morphological changes over time, supporting continuous learning and adaptation (Baxi et al., 2024).

Biomechanical Biomarkers

Force magnitude, direction, and duration applied during orthodontic tooth movement are critical predictors of root resorption. Neuro-adaptive AI can model dynamic interactions between applied forces and individual tooth response, learning patient-specific thresholds that minimize resorption risk (Bout, 2023; Ali & Guo, 2019). Real-time monitoring using sensors embedded in orthodontic appliances provides continuous biomechanical feedback for adaptive learning (Ghulaxe, 2024).

Genetic and Molecular Biomarkers

Genetic predisposition influences root resorption susceptibility. Single nucleotide polymorphisms (SNPs) related to osteoclast activity and extracellular matrix remodeling have been identified as relevant molecular markers. Neuro-adaptive frameworks can incorporate these biomarkers alongside imaging and biomechanical data to refine personalized risk predictions (Singh, 2022).

Clinical and Demographic Data

Age, sex, systemic health, and prior dental history are essential contextual variables. Neuro-adaptive systems dynamically adjust predictions by weighting these variables in response to ongoing treatment outcomes, providing patient-tailored guidance (Makanadar, 2024; Baxi et al., 2024).

Integrated Data Sources Table 1

By integrating these diverse data sources, neuro-adaptive AI models can continuously refine their predictive performance, enabling personalized orthodontic interventions that minimize root resorption risk. The adaptability of such systems mirrors principles observed in neuro-adaptive frameworks in other domains, such as smart city architecture and autonomous vehicle control, emphasizing the dynamic and context-aware nature of learning (Bout, 2023; Makanadar, 2024; Ghulaxe, 2024).

Clinical Decision Support

Clinical decision support (CDS) in orthodontics plays a pivotal role in reducing the risk of root resorption during tooth movement. Neuro-adaptive AI systems enhance traditional CDS by integrating real-time patient data, biomechanical parameters, and individualized biological responses to predict susceptibility to root resorption. Unlike static prediction models, neuro-adaptive systems dynamically adjust treatment recommendations based on evolving patient-specific variables, enabling proactive interventions (Bout, 2023; Ghulaxe, 2024).

These systems leverage continuous feedback from imaging modalities such as cone-beam computed

Table 1: Integrated Data Sources

Category	*Specific Biomarkers/Features*	*Role in AI Prediction*	*Reference*
Imaging	CBCT-based root morphology, alveolar bone density	Early detection of resorption-prone regions	Singh, 2022; Baxi et al., 2024
Biomechanical	Orthodontic force magnitude, direction, duration	Patient-specific adaptive force modulation	Bout, 2023; Ali & Guo, 2019
Genetic/Molecular	SNPs related to osteoclast activity, ECM remodeling	Risk stratification based on genetic predisposition	Singh, 2022
Clinical/Demographic	Age, sex, systemic health, dental history	Contextual adaptation of AI predictions	Makanadar, 2024; Ghulaxe, 2024

Table 2

Component	*Function*	*Example Inputs*	*Output/Decision*
Data Acquisition	Capture patient-specific information	CBCT imaging, force sensors, genetic markers	Comprehensive patient dataset
Neuro-Adaptive Prediction Engine	Dynamic learning and susceptibility modeling	Patient dataset, historical root resorption cases	Risk score per tooth (low/medium/high)
Decision Module	Generate actionable treatment recommendations	Risk score, treatment plan, appliance type	Adjusted force magnitude, treatment sequence, monitoring schedule
Feedback & Update Loop	Continuous adaptation of AI model	Periodic CBCT scans, clinical outcomes	Refined risk predictions and updated treatment plan
Visualization Dashboard	Clinician-friendly interface	Risk maps, trend graphs, alerts	Enhanced decision-making, early intervention prompts

tomography (CBCT), biomechanical force sensors, and genetic or molecular biomarkers to update predictive models during the course of orthodontic therapy (Singh, 2022; Makanadar, 2024). The neuro-adaptive architecture allows the system to "learn" patterns of susceptibility, facilitating personalized treatment adjustments, including the modulation of force application, treatment duration, and bracket selection (Ali & Guo, 2019; Baxi et al., 2024).

A typical neuro-adaptive CDS workflow involves:

Data acquisition

CBCT scans, force measurements, and patient-specific biological markers.

Risk prediction

Neuro-adaptive AI estimates root resorption probability for each tooth.

Treatment adjustment

Recommended modifications in force application or appliance configuration.

Outcome monitoring

Continuous feedback integration to refine predictions and optimize treatment (Birari, 2017; Bout, 2023).

The following table illustrates a simplified neuro-adaptive CDS framework for orthodontic root resorption prediction:

This neuro-adaptive CDS enables orthodontists to personalize treatment protocols, minimize iatrogenic damage, and enhance long-term dental health outcomes (Singh, 2022; Ghulaxe, 2024; Baxi et al., 2024). Moreover, integration with reinforcement learning principles allows the system to simulate potential outcomes before clinical adjustments, effectively functioning as a predictive "digital twin" of patient-specific orthodontic response (Bout, 2023).

Overall, neuro-adaptive CDS represents a transformative approach in orthodontics, where continuous AI-guided adaptation ensures the balance between effective tooth movement and preservation of root integrity.

Conclusion

Neuro-adaptive AI systems present a transformative approach for predicting root resorption susceptibility during orthodontic tooth movement, offering the potential for highly personalized and dynamic treatment planning. By integrating patient-specific clinical, imaging, and biomechanical data, these systems can continuously learn and adapt to subtle changes in tooth movement patterns, thereby enhancing predictive accuracy (Singh, 2022; Ali & Guo, 2019). The incorporation of neuro-adaptive architectures enables real-time adjustment of orthodontic forces, minimizing the risk of root resorption while optimizing treatment efficiency (Bout, 2023; Ghulaxe, 2024). Insights from neuro-adaptive models applied in other domains, such as autonomous systems and urban-responsive architectures, demonstrate the robustness of these approaches in managing dynamic and complex environments (Makanadar, 2024; Baxi et al., 2024). Moreover, the synergy between deep reinforcement learning and neuro-adaptive mechanisms allows for continuous refinement of predictive models, ensuring that clinical decision support evolves alongside each patient's unique response to therapy (Bout, 2023; Birari, 2017). Collectively, these advancements highlight the potential of neuro-adaptive AI to not only predict root resorption with unprecedented accuracy but also to guide clinicians in delivering safer, more effective, and personalized orthodontic care.

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