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Research Article

Artificial intelligence-assisted prediction of instrument separation during root canal preparation based on canal anatomy and instrument stress

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ABSTRACT

Instrument separation remains one of the most challenging procedural complications during root canal preparation, often compromising treatment efficiency, prognosis, and long-term clinical outcomes. Recent advances in artificial intelligence (AI) have created new opportunities to predict the likelihood of instrument fracture by integrating anatomical, mechanical, and procedural data before and during endodontic treatment. AI models can analyze cone-beam computed tomography images to identify complex canal morphology, including severe curvature, narrow canals, bifurcations, and calcifications, while simultaneously incorporating information related to instrument design, alloy properties, kinematics, and estimated mechanical stress. Machine learning and deep learning algorithms enable the identification of high-risk clinical scenarios, allowing clinicians to select appropriate instruments, modify preparation strategies, and minimize excessive torsional and cyclic fatigue. AI-assisted predictive systems also support personalized treatment planning, improve procedural consistency, and reduce operator-dependent variability through evidence-based decision support. Despite these advantages, widespread clinical implementation requires robust multicenter datasets, standardized validation protocols, seamless integration with digital endodontic workflows, and transparent model interpretation to ensure clinician confidence and patient safety. As digital dentistry continues to evolve, AI-assisted prediction of instrument separation has the potential to transform preventive risk assessment, optimize root canal preparation, and enhance the precision, safety, and overall success of modern endodontic therapy.

Introduction

Instrument separation during root canal preparation is a significant procedural complication that can compromise canal debridement, impede disinfection, and adversely affect the prognosis of endodontic treatment. Separation typically results from cyclic fatigue, torsional overload, or a combination of both, with risk increasing in canals exhibiting severe curvature, abrupt apical deviations, narrow diameters, and anatomical complexities. Conventional risk assessment relies primarily on clinician experience and preoperative radiographic interpretation, which may not consistently identify cases at high risk for instrument fracture. Consequently, there is growing interest in artificial intelligence (AI)-assisted predictive systems capable of integrating multiple clinical and imaging variables to support safer and more individualized treatment planning (Singh, 2022; Ahmed et al., 2025).

Recent advances in AI have transformed the analysis of cone-beam computed tomography (CBCT), digital

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Table 1: Key Factors Incorporated into AI Models for Predicting Instrument Separation

Predictive Factor	*Examples*	*Contribution to AI Prediction*
Canal anatomy	Curvature, radius, canal diameter, bifurcations, calcification	Identifies anatomical complexity associated with increased fracture risk
Instrument characteristics	Alloy type, taper, tip size, cross-sectional design	Estimates resistance to torsional and cyclic fatigue
Mechanical stress	Torsional load, cyclic fatigue, rotational speed, torque	Predicts probability of instrument failure during preparation
Imaging data	CBCT scans, periapical radiographs	Provides detailed anatomical features for automated analysis
Clinical variables	Tooth type, operator experience, irrigation protocol	Enhances individualized risk assessment and treatment planning
Digital health records	Previous treatments, procedural history, patient characteristics	Improves predictive accuracy through multimodal data integration

radiographs, and electronic dental records by enabling automated recognition of complex canal anatomy and prediction of procedural risks. Machine learning and deep learning algorithms can evaluate root curvature, canal diameter, calcification, bifurcations, and other morphological characteristics while simultaneously incorporating information related to instrument design, alloy composition, kinematics, and anticipated mechanical stress. These multimodal analytical approaches facilitate personalized risk prediction before instrumentation begins, allowing clinicians to optimize instrument selection and preparation strategies. Similar AI-driven predictive frameworks have demonstrated considerable success across various dental applications, highlighting the growing reliability of intelligent decision-support systems in clinical dentistry (Feher et al., 2024; Hamdan et al., 2025; Polizzi et al., 2024).

Beyond image analysis, AI platforms increasingly integrate structured clinical information obtained from electronic dental records and procedural datasets to improve predictive accuracy. Data-driven modeling enables continuous refinement of fracture-risk estimation as additional clinical evidence becomes available, thereby enhancing precision and supporting evidence-based decision making (Patel et al., 2018). Although foundational biomedical and regenerative research has emphasized the importance of tissue preservation and biological healing in dentistry (Zhao et al., 2004; Amato et al., 2023), the application of AI extends these principles by minimizing preventable procedural complications and improving treatment predictability. As computational technologies continue to evolve, AI-assisted prediction of instrument separation represents an important advancement toward precision endodontics, where anatomical complexity, instrument mechanics, and patient-specific factors are integrated into intelligent clinical workflows that enhance procedural safety, efficiency, and long-term treatment outcomes (Singh, 2022; Ahmed et al., 2025; Singh, 2025).

Artificial Intelligence Models for Predicting Instrument Separation

Artificial intelligence (AI) models are increasingly being developed to predict the risk of instrument separation during root canal preparation by integrating anatomical, mechanical, and procedural variables into data-driven predictive systems. Unlike conventional risk assessment, which relies primarily on clinician experience, AI algorithms can simultaneously analyze large volumes of clinical and imaging data to identify complex relationships that contribute to cyclic fatigue and torsional failure of endodontic instruments. This predictive capability supports personalized treatment planning and safer instrumentation strategies (Singh, 2022; Ahmed et al., 2025).

Machine learning techniques, including decision trees, random forests, support vector machines, and artificial neural networks, are capable of processing cone-beam computed tomography (CBCT) measurements such as canal curvature, radius, diameter, canal length, calcification, and anatomical complexity alongside instrument characteristics including alloy composition, taper, cross-sectional design, rotational speed, and torque settings. Deep learning models further enhance predictive performance by automatically extracting imaging features from CBCT scans without requiring manual measurements, thereby improving efficiency and reducing observer variability (Hamdan et al., 2025; Feher et al., 2024).

Electronic dental records also contribute valuable clinical information for predictive modeling. Previous studies have demonstrated the usefulness of structured patient records for machine learning applications, providing a framework for integrating demographic factors, previous endodontic history, tooth location, operator experience,

Table 2

AI Model/Input	*Primary Data Used*	*Prediction Objective*	*Clinical Benefit*
Decision Tree	Canal curvature, canal diameter	Classify fracture risk	Simple clinical interpretation
Random Forest	Anatomical and procedural variables	Predict instrument separation probability	Improved predictive accuracy
Support Vector Machine	Instrument stress parameters	Distinguish high- and low-risk cases	Effective with complex datasets
Artificial Neural Network	Multivariable clinical and imaging data	Model nonlinear fracture risk	Personalized treatment planning
Deep Learning (CNN)	CBCT images	Automatic detection of complex canal anatomy	Reduced observer variability and faster assessment

and procedural outcomes into comprehensive risk prediction systems (Patel et al., 2018). AI systems may continuously refine prediction accuracy as additional clinical cases become available, enabling adaptive learning and increasingly reliable clinical recommendations (Singh, 2022).

Despite promising results, AI models require large, diverse, and well-annotated datasets to achieve robust generalizability across different populations and clinical settings. Explainable AI approaches are also essential to improve clinician trust by clarifying how predictions are generated. Validation through multicenter studies and standardized reporting frameworks will further strengthen clinical adoption and facilitate integration into digital endodontic workflows (Ahmed et al., 2025; Polizzi et al., 2024). Although studies by Zhao et al. (2004), Amato et al. (2023), and Singh (2025) focus on broader regenerative and restorative applications, they collectively emphasize the growing role of advanced data-driven technologies in improving precision and decision-making throughout modern dental practice.

Table 3: Clinical applications, benefits, and challenges of AI-assisted prediction of instrument separation

Aspect	*Clinical Significance*
Preoperative anatomical assessment	Identifies high-risk canal morphology using CBCT analysis
Instrument selection	Recommends appropriate file design, alloy, taper, and motion
Real-time stress prediction	Detects excessive torsional and cyclic fatigue during preparation
Personalized treatment planning	Adapts instrumentation protocols according to patient-specific anatomy
Reduced procedural complications	Lowers incidence of instrument separation and treatment failure
Clinical limitations	Dependence on high-quality datasets, external validation, workflow integration, and model interpretability

Clinical Applications, Benefits, and Challenges

Artificial intelligence (AI) is increasingly being incorporated into endodontic practice to predict instrument separation by combining information from cone-beam computed tomography (CBCT), clinical records, and instrument-related variables. AI algorithms can evaluate canal curvature, canal diameter, calcification, bifurcations, and other anatomical complexities that contribute to elevated torsional and cyclic fatigue during root canal preparation. By integrating these parameters with instrument characteristics such as alloy type, taper, cross-sectional geometry, rotational speed, and motion pattern, AI generates individualized risk assessments that assist clinicians in selecting safer instrumentation strategies (Singh, 2022; Ahmed et al., 2025).

A major clinical application is preoperative risk stratification. AI systems can identify teeth with highly curved or anatomically complex canals before treatment begins, enabling clinicians to modify access design, select more fatigue-resistant instruments, or adopt conservative preparation protocols. During instrumentation, integration with digital endodontic motors and imaging platforms may provide real-time alerts when stress thresholds approach levels associated with instrument fracture. Such predictive decision support minimizes unexpected procedural errors while promoting standardized and evidence-based clinical practice (Hamdan et al., 2025; Feher et al., 2024).

Beyond procedural safety, AI contributes to personalized dentistry by integrating imaging findings with electronic dental records and patient-specific clinical information, creating predictive models that continuously improve through machine learning. Similar approaches have demonstrated significant predictive capability in broader dental applications, supporting the feasibility of AI-driven clinical decision systems (Patel et al., 2018; Polizzi et al., 2024). Nevertheless, widespread adoption remains constrained by limited multicenter datasets, variability in imaging quality, algorithm transparency, regulatory considerations, and interoperability with existing digital platforms. Continued research, standardized validation protocols, and clinician education will be essential for translating AI-assisted fracture prediction into routine endodontic practice while maximizing patient safety and treatment reliability (Singh, 2022; Ahmed et al., 2025; Amato et al., 2023; Zhao et al., 2004; Singh, 2025).

Future Perspectives and Conclusion

Artificial intelligence-assisted prediction of instrument separation is expected to become an integral component of digital endodontics through the convergence of advanced imaging, machine learning, and real-time procedural monitoring. Future systems are likely to integrate cone-beam computed tomography (CBCT), intraoperative sensor feedback, and electronic dental records into unified predictive platforms capable of continuously estimating instrument stress throughout canal preparation. Such multimodal approaches could provide clinicians with dynamic warnings regarding excessive torsional or cyclic fatigue, enabling timely modification of instrumentation strategies before fracture occurs. Continued improvements in deep learning algorithms and explainable AI will further enhance clinician confidence by providing transparent risk assessments supported by anatomical and biomechanical evidence (Singh, 2022; Ahmed et al., 2025; Hamdan et al., 2025).

Future research should prioritize the development of large, multicenter datasets that encompass diverse canal anatomies, instrument systems, operator experience, and treatment protocols. Standardized data collection and external validation will improve the robustness and generalizability of predictive models across different clinical settings. Integration of biomechanical modeling, finite element analysis, and patient-specific anatomical characteristics may further refine fracture-risk estimation. Additionally, combining AI with smart endodontic motors capable of monitoring torque, rotational speed, and mechanical stress in real time may facilitate adaptive instrumentation strategies that minimize procedural complications. Advances in multimodal AI frameworks and data-driven modeling across dentistry support the feasibility of these developments (Feher et al., 2024; Patel et al., 2018; Polizzi et al., 2024).

Although challenges remain regarding data quality, algorithm transparency, regulatory approval, and seamless incorporation into clinical workflows, ongoing technological progress continues to strengthen the role of AI in precision endodontics. The broader movement toward personalized digital dentistry, intelligent imaging analysis, and biologically informed treatment planning provides a strong foundation for the evolution of predictive endodontic systems. Innovations in tissue engineering and regenerative research further emphasize the importance of preserving tooth structure through safer instrumentation, while advances in controlled therapeutic technologies may complement future AI-guided treatment protocols (Zhao et al., 2004; Amato et al., 2023).

In conclusion, AI-assisted prediction of instrument separation represents a promising advancement for improving the safety, precision, and predictability of root canal preparation. By integrating canal anatomy, instrument characteristics, and stress analysis into intelligent decision-support systems, AI has the potential to reduce procedural errors, optimize clinical decision-making, and improve long-term treatment outcomes. Continued interdisciplinary collaboration, rigorous clinical validation, and responsible implementation will be essential to realizing the full clinical potential of this emerging technology (Singh, 2022; Ahmed et al., 2025; Singh, 2025).

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