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Scoping Review

CNN-POWERED ARCHWIRE ROBOTICS TO TRANSFORM ORTHODONTIC APPLIANCE MANUFACTURING WITH STATE-OF-THE-ART AUTOMATION

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ABSTRACT

Background. Malocclusion, a prevalent dental disorder, disrupts tooth alignment, mastication, speech, and aesthetics, significantly affecting self-confidence. Its high prevalence in Asian populations, particularly in Indonesia, where 80% of individuals are affected, necessitates more precise and efficient orthodontic solutions. Conventional *archwire* bending methods remain prone to inaccuracies, contributing to treatment failures in over 37% of cases. This study explores the integration of Convolutional Neural Networks (CNNs) into robotic *archwire* bending systems as a transformative innovation to enhance orthodontic precision and efficiency.
Research Method. A comprehensive literature review was conducted using major scientific databases, including PubMed, ScienceDirect, SCOPUS, ProQuest, and EBSCO, focusing on studies published from 2017 onward. Ten relevant articles were analyzed to evaluate CNN applications in robotic systems and their potential to improve orthodontic appliance production accuracy.
Findings. The CNN-driven robotic system operates through two primary subsystems—data processing and mechanical execution supported by 3D modeling, CAD-based stress analysis, and Finite Element Method (FEM) validation. In the mechanical phase, robotic arms guided by sEMG signals and optimized through CNN-based motion recognition ensure superior precision in *archwire* shaping. This system minimizes human error, enhances treatment accuracy, and significantly reduces clinical time.
Conclusion. CNN-integrated robotic *archwire* bending represents a breakthrough in orthodontic practice, enabling highly accurate, efficient, and patient-centered treatment outcomes. This innovation aligns with Sustainable Development Goal (SDG) 3 on Good Health and Well-Being, offering a substantial leap toward the future of digital orthodontics.

Keywords: Malocclusion, Orthodontic Robotics, Convolutional Neural Networks, *Archwire* Bending, Artificial Intelligence, Digital Dentistry.

BACKGROUND

Malocclusion, a pressing dental issue, disrupts tooth alignment and affects chewing, speech, and aesthetics, impacting self–confidence [1,2]. Often accompanied by dental crowding, it complicates cleaning and increases the risk of caries and periodontitis [1]. This problem is particularly common in Asian populations due to the elliptical shape of their dental arches, which restricts space for 32 permanent teeth and leads to crowding [3].

In Indonesia, Indonesian Health Survey in 2023, reveals that malocclusion affects about 80% of people, with a notable 15.6% prevalence among children aged 12–15 years. Addressing this issue, orthodontic treatment becomes the gold standard; however, traditional orthodontic treatment involves precise wire bending and retainers to correct and maintain tooth alignment [3]. However, manual *archwire* adjustments often fall short, leading to treatment failures in 37.53% of maxillary and 38.67% of mandibular cases due to discrepancies [4]. To overcome these challenges, CNN driven *archwire* bending robots present a revolutionary solution. By enhancing precision and efficiency, this technology reduces treatment times and increases patient satisfaction [5].

Although malocclusion remains one of the most prevalent oral health problems globally and orthodontic treatment is considered the gold standard for its management, significant challenges persist in achieving precise *archwire* fabrication. Conventional orthodontic procedures still rely heavily on manual wire bending performed by clinicians or technicians, which is susceptible to human error, operator variability, and inconsistencies in *archwire* geometry. Previous studies have reported substantial treatment failures resulting from discrepancies between the planned and fabricated *archwire* shapes. While advances in artificial intelligence (AI), robotics, and computer vision have been introduced in various medical and dental applications, the integration of deep learning–based robotic systems, particularly those utilizing Convolutional Neural Networks (CNNs) for automated orthodontic *archwire* bending, remains limited [6]. Furthermore, existing orthodontic research has predominantly focused on treatment outcomes and appliance design rather than investigating intelligent robotic solutions capable of improving fabrication accuracy and standardization. Therefore, a significant research gap exists regarding the application of CNN-driven robotic technology as an automated and precision-oriented alternative to conventional *archwire* bending methods.

The novelty of this research lies in the development and application of a CNN-driven *archwire* bending robotic system for orthodontic treatment. Unlike conventional approaches that depend on manual manipulation and practitioner expertise, this study introduces an artificial intelligence based framework capable of automatically recognizing *archwire* configurations and executing precise bending procedures through robotic mechanisms. The integration of deep learning algorithms with robotic orthodontic fabrication represents an emerging interdisciplinary approach that combines dentistry, artificial intelligence, and automation engineering. Moreover, this study shifts the focus from merely evaluating orthodontic treatment outcomes to optimizing the manufacturing process of orthodontic appliances themselves. By leveraging CNN technology for real-time pattern recognition and robotic control, the proposed system offers a novel strategy to minimize fabrication discrepancies, enhance reproducibility, and support personalized orthodontic treatment planning [7].

This research contributes to both scientific knowledge and clinical orthodontic practice. From a scientific perspective, it expands the emerging body of literature on AI-assisted dentistry by providing evidence for the feasibility of integrating CNN-based machine learning with robotic orthodontic systems. The study also establishes a foundation for future investigations into intelligent automation within dental healthcare.

From a clinical perspective, the proposed robotic *archwire* bending system has the potential to improve treatment precision, reduce human-related fabrication errors, decrease orthodontic treatment duration, and enhance overall treatment predictability. These improvements may ultimately increase patient satisfaction and treatment success rates. Furthermore, by supporting more efficient and standardized orthodontic workflows, the technology aligns with global healthcare innovation initiatives and contributes to the achievement of Sustainable Development Goal (SDG) 3, which aims to ensure healthy lives and promote well-being for all through the adoption of advanced healthcare technologies. This study explores the integration of Convolutional Neural Networks (CNNs) into robotic *archwire* bending systems as a transformative innovation to enhance orthodontic precision and efficiency.

RESEARCH METHOD

This study employed a narrative literature review approach to explore the potential integration of Convolutional Neural Networks (CNNs) into robotic *archwire* bending systems for orthodontic appliance production. The review was conducted to synthesize current evidence regarding the application of artificial intelligence, machine learning, and robotic technologies in orthodontics, with a particular focus on improving the accuracy, precision, and efficiency of *archwire* fabrication.

A systematic search strategy was performed across several internationally recognized scientific databases, including PubMed, ScienceDirect, SCOPUS, ProQuest, and EBSCO. These databases were selected because they provide comprehensive coverage of peer-reviewed literature in dentistry, biomedical engineering, artificial intelligence, and healthcare technology. The literature search was conducted using a combination of keywords and Boolean operators, including “convolutional neural network,” “CNN,” “deep learning,” "*archwire* robotics," "robotic wire bending," "malocclusion," "orthodontic appliance," "fixed orthodontic appliance," and "removable orthodontic appliance." Search terms were adapted according to the indexing system of each database to maximize retrieval sensitivity.

To ensure the relevance and contemporary nature of the evidence, only articles published between January 2017 and December 2025 were considered for inclusion. This period was selected because of the rapid advancement of artificial intelligence and robotic technologies in healthcare during the last decade. Eligible studies included original research articles, experimental studies, engineering developments, clinical investigations, and review papers that discussed CNN applications, robotic systems, automated manufacturing technologies, or orthodontic appliance production. Articles not published in English, conference abstracts without full-text availability, editorials, opinion papers, and studies unrelated to orthodontic robotics or AI-assisted dental manufacturing were excluded.

The study selection process was conducted in several stages. First, titles and abstracts identified through database searching were screened for relevance. Second, full-text articles meeting the preliminary inclusion criteria were retrieved and assessed in detail. Duplicate publications were removed before the final selection. A total of ten highly relevant articles were included in the final review after applying the eligibility criteria.

Data extraction was performed using a standardized review matrix. Information collected from each article included publication year, study design, technological approach, CNN architecture, robotic system characteristics, orthodontic application, reported outcomes, advantages, limitations, and implications for clinical practice. The extracted findings were subsequently categorized into three major themes: (1) fundamental concepts and applications of CNN technology in healthcare and dentistry; (2) current workflows and challenges in orthodontic *archwire* fabrication and robotic bending systems; and (3) the potential effectiveness of CNN-integrated robotic systems in improving orthodontic appliance accuracy, precision, efficiency, and treatment outcomes.

A thematic synthesis approach was employed to analyze and integrate the findings across studies. The evidence was critically evaluated to identify current technological developments, existing research gaps, implementation challenges, and future opportunities for AI-driven orthodontic manufacturing. Through this comprehensive analysis, the review aimed to provide a conceptual framework for the development of intelligent robotic *archwire* systems capable of supporting precision orthodontics and advancing the digital transformation of dental healthcare.

FINDINGS

The *archwire* bending robotic system revolutionizes orthodontics with its dual powerhouse subsystems: data processing and mechanical processing. This sophisticated integration not only streamlines but also ensures exceptional precision in orthodontic treatments through a meticulously orchestrated workflow. Imaging and modeling: the process starts with capturing the patient’s dental condition using 3D cone–beam computed tomography (CBCT). This data is used to create a detailed study model through 3D printing. Design and analysis: the model is equipped with 'bracket and tube elements' and *archwire*, then analyzed using computer–aided design (CAD) software. CAD evaluates compression, elasticity, and deformation to create an *archwire* bending diagram [6]. Validation: finite element method (FEM) algorithms refine this design by simulating various scenarios, ensuring forces are evenly distributed to avoid pressure concentration and facilitate effective tooth movement [7].

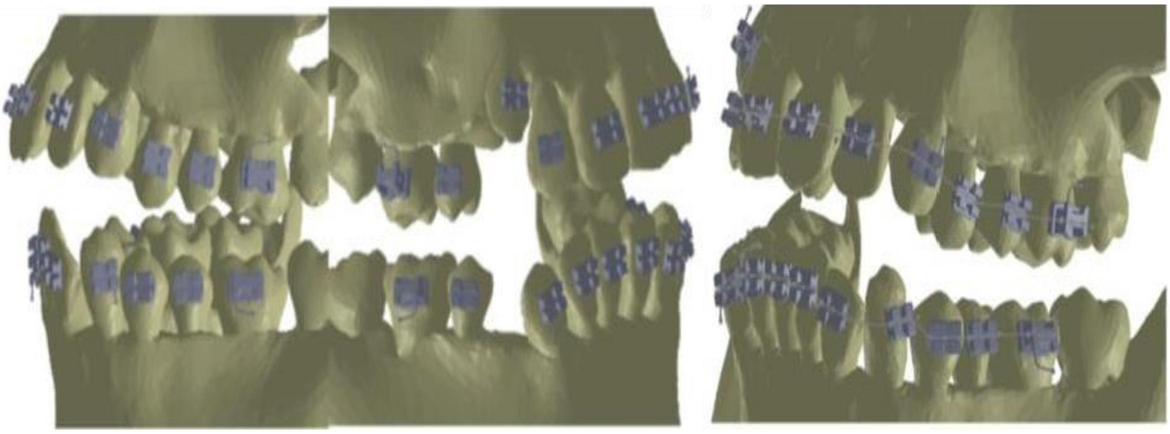

Figure 1 Virtual localization of 'bracket and tube elements' (left) and the path-based curve formed by the orthodontic *archwire*.

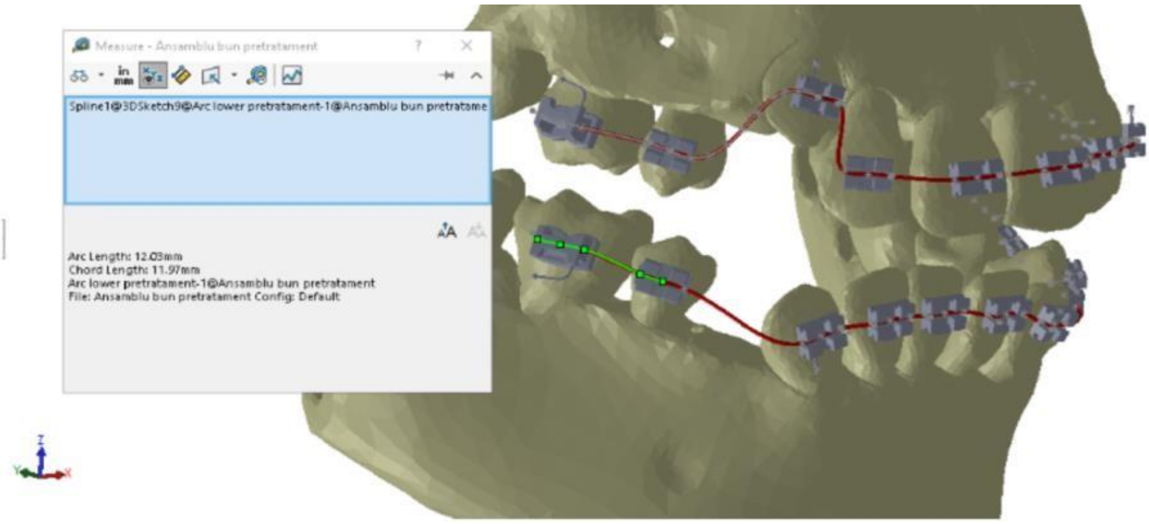

Figure 2 Analysis of the path–based curve through the FEM algorithm.

DISCUSSIONS

Mechanical Processing Workflow

Execution: the design is implemented by two robotic arms that precisely shape the *archwire*. Under the guidance of a microcontroller and wireless communication, these arms are fitted with a six–axis configuration and driven by servo motors, providing precise control over their position, speed, and acceleration [8,9]. Refinement: in order to obtain perfect the *archwire*'s shape, constraint sensors and a resistive heating system, fine–tune mechanical and thermal adjustments, achieving precise and accurate final results (2). In the mechanical processing phase, control is significantly enhanced through the use of surface electromyographic (sEMG) signals. These signals are captured via sparse multichannel systems and are further refined using convolutional neural networks (CNNs), a subset of artificial intelligence (AI) specializing in spatial learning through deep learning methodologies [10].

Figure 3 Machine processing model consisting of two robotic arms equipped with pliers for bending the *archwire* with perfect accuracy and precision.

The integration of CNNs into the sEMG acquisition system (EAS) involves a structured preprocessing workflow based on five core principles: annotation, augmentation, segmentation, validation, and testing. These stages are designed to optimize the robotic arms' movements in controlling *archwire* bending, ensuring that the resulting orthodontic appliances precisely address the patient's malocclusion. Annotation and augmentation: this phase involves filtering and refining movement data from various skilled practitioners who handle different types of malocclusion cases. This data is crucial for training the CNN to understand and replicate the precise movements required for effective *archwire* bending (10). Normalization and downsampling: the filtered data is then normalized and downsampled to ensure that it is ideal for CNN training. This process guarantees that the data used is the most efficient and specific, thereby facilitating a more effective learning process for the CNN. Segmentation: this step simplifies movement cycles and maps them onto a grid of discrete pixels, allowing the CNN to analyze alignment based on amplitude. The CNN then develops its own rhythm for motion recognition, enhancing its ability to determine precise movement cycles (10).

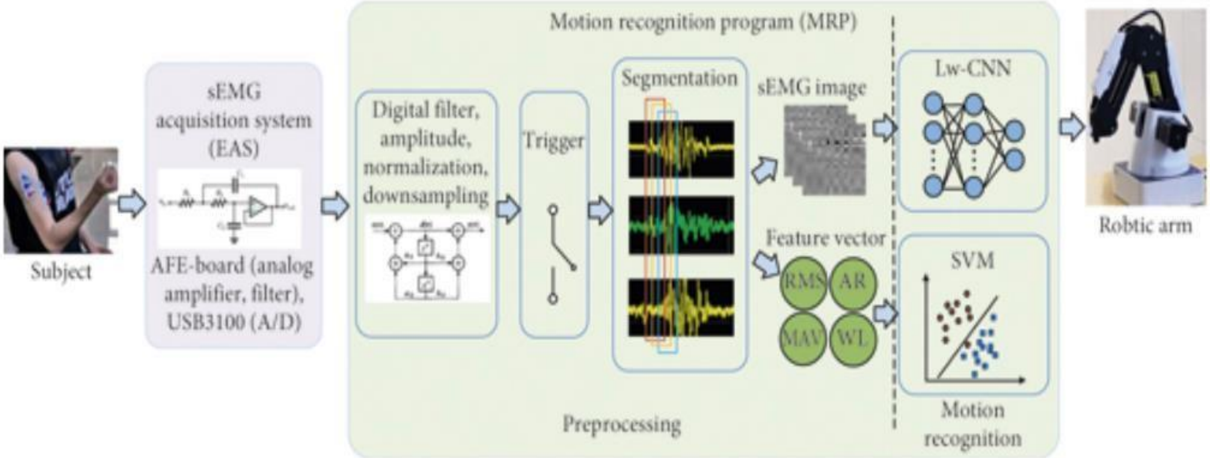

Figure 4 Operational principles of CNN in the *Archwire* Bending System, illustrated through two main stages: EAS and MRP (Motion Recognition Program).

As a result, this CNN driven learning process equips the robotic arms with the ability to execute precise, controlled movements for bending the *archwire*, achieving optimal alignment and functionality for orthodontic appliances.

Study Limitations

Several limitations should be considered when interpreting the findings of this review. First, the number of studies specifically investigating the integration of Convolutional Neural Networks (CNNs) with robotic *archwire* bending systems remains limited. Although substantial literature exists regarding artificial intelligence in dentistry and robotic automation in manufacturing, relatively few studies have directly examined their combined application in orthodontic appliance production. This limitation reflects the emerging nature of the field and restricts the availability of high-quality evidence for comprehensive evaluation.

Second, the reviewed studies exhibited considerable heterogeneity in terms of research objectives, technological platforms, CNN architectures, robotic configurations, and outcome measurements. Such variability makes direct comparison between studies challenging and limits the ability to establish standardized conclusions regarding the effectiveness of CNN-driven robotic systems in orthodontics.

Third, most available studies were conducted in laboratory, simulation, or prototype-development settings rather than real-world clinical environments. Consequently, the reported improvements in accuracy, precision, and efficiency may not fully represent the performance of these systems when implemented in routine orthodontic practice. Factors such as patient-specific anatomical variations, operator acceptance, clinical workflow integration, and maintenance requirements remain insufficiently explored.

Fourth, this review included only articles published in English and indexed within selected academic databases. Therefore, relevant studies published in other languages or databases may not have been captured, potentially introducing publication bias and limiting the comprehensiveness of the evidence synthesis. Finally, because this study employed a narrative literature review design, quantitative synthesis and meta-analysis were not performed. As a result, the magnitude of the potential benefits associated with CNN-integrated robotic *archwire* systems could not be statistically estimated.

Recommendations for Clinical Practice

Despite the current limitations, the findings suggest that CNN-integrated robotic *archwire* bending systems have considerable potential to enhance orthodontic appliance manufacturing. Orthodontic clinics and dental laboratories should begin exploring digital orthodontic workflows that incorporate artificial intelligence, computer-aided design, and robotic fabrication technologies. Such innovations may improve appliance precision, reduce operator-dependent variability, and support more predictable treatment outcomes.

Dental professionals should also strengthen interdisciplinary collaboration with experts in artificial intelligence, robotics, biomedical engineering, and computer science to facilitate the development of clinically relevant and user-friendly automated orthodontic systems. In addition, educational institutions may consider incorporating digital dentistry, machine learning, and healthcare automation into orthodontic training programs to prepare future practitioners for technology-driven clinical environments.

Recommendations for Future Research

Future studies should move beyond conceptual and prototype-level investigations toward large-scale experimental and clinical validation studies. Prospective clinical trials are needed to compare CNN-driven robotic *archwire* bending systems with conventional manual fabrication methods in terms of treatment accuracy, efficiency, patient satisfaction, treatment duration, and long-term clinical outcomes.

Researchers should also investigate the integration of three-dimensional dental imaging, intraoral scanning, and personalized treatment planning algorithms with CNN-based robotic systems to create fully automated orthodontic manufacturing workflows. Furthermore, studies evaluating the economic feasibility, cost-effectiveness, implementation barriers, and user acceptance of these technologies are essential to support widespread adoption in clinical settings.

As artificial intelligence continues to evolve, future research should explore advanced deep learning architectures, real-time adaptive learning systems, and intelligent feedback mechanisms capable of continuously improving robotic performance based on clinical outcomes. Such developments may contribute significantly to the advancement of precision orthodontics and the broader digital transformation of dental healthcare.

CONCLUSION

Manual *archwire* bending by orthodontists or technicians frequently requires numerous revisions, resulting in substantial time loss and elevated medical costs for each patient. In stark contrast, the *archwire* bending robotic system delivers exceptional precision and dramatically shortens treatment times. This cutting-edge technology ensures superior accuracy, significantly enhances patient satisfaction, and offers unparalleled comfort by streamlining the treatment process. Embracing this advanced system not only optimizes efficiency but also provides a transformative improvement in the overall patient experience, making it a compelling choice for modern orthodontic care.

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