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ARTIFICIAL INTELLIGENCE IN ORTHODONTICS: INTEGRATION WITH HERBST APPLIANCE THERAPY FOR DIAGNOSIS, TREATMENT PLANNING AND OUTCOME EVALUATION

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ABSTRACT

The integration of artificial intelligence (AI) into orthodontics is transforming diagnostic and therapeutic approaches, particularly in the management of skeletal Class II malocclusion with the Herbst appliance. This article reviews the application of AI-based methods — including machine learning (ML) and convolutional neural networks (CNN) — in Herbst appliance therapy, encompassing automated cephalometric landmark detection, skeletal maturation assessment, treatment outcome prediction, and post-treatment stability evaluation. A clinical study of 90 patients aged 10–16 years treated with the Herbst appliance was conducted. AI-assisted cephalometric analysis demonstrated a mean landmark detection error of 1.21±0.34 mm versus 2.18±0.61 mm by manual method ($p<0.001$). AI-predicted mandibular advancement outcomes matched actual results with 91.3% accuracy. The study confirms that AI serves as a powerful complementary tool in Herbst appliance orthodontic care, enhancing precision, consistency, and treatment efficiency.

Keywords: artificial intelligence, machine learning, Herbst appliance, orthodontics, Class II malocclusion, cephalometric analysis, convolutional neural network, skeletal maturation, treatment planning.

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ИСКУССТВЕННЫЙ ИНТЕЛЛЕКТ В ОРТОДОНТИИ: ИНТЕГРАЦИЯ С ТЕРАПИЕЙ АППАРАТОМ ГЕРБСТА ДЛЯ ДИАГНОСТИКИ, ПЛАНИРОВАНИЯ ЛЕЧЕНИЯ И ОЦЕНКИ РЕЗУЛЬТАТОВ

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АННОТАЦИЯ

Интеграция искусственного интеллекта (ИИ) в ортодонтию трансформирует диагностические и терапевтические подходы, особенно при лечении скелетной аномалии прикуса II класса с использованием аппарата Гербста. В данной статье рассматривается применение методов, основанных на ИИ — включая машинное обучение (ML) и сверточные нейронные сети (CNN) — в терапии аппаратом Гербста, охватывающее автоматизированное определение цефалометрических ориентиров, оценку скелетной зрелости, прогнозирование результатов лечения и оценку стабильности после лечения Проведено клиническое исследование с участием 90 пациентов в возрасте 10–16 лет, проходивших лечение с использованием аппарата Гербста. Цефалометрический анализ с применением ИИ показал среднюю ошибку определения ориентиров 1,21±0,34 мм по сравнению с 2,18±0,61 мм при ручном методе ($p<0,001$). Прогнозируемые с помощью ИИ результаты выдвижения нижней челюсти совпали с фактическими результатами с точностью 91,3% Исследование подтверждает, что ИИ является мощным вспомогательным инструментом в ортодонтическом лечении с применением аппарата Гербста, повышая точность, воспроизводимость и эффективность лечения.

Ключевые слова: искусственный интеллект, машинное обучение, аппарат Гербста, ортодонтия, аномалия прикуса II класса, цефалометрический анализ, сверточная нейронная сеть, скелетная зрелость, планирование лечения.

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INTRODUCTION

Class II malocclusion — characterized by mandibular retrusion relative to the maxilla — affects approximately 15–30% of the global population and represents one of the most common skeletal discrepancies encountered in orthodontic practice [1]. Among the functional appliances available for its correction during the growth period, the Herbst appliance has established itself as a highly effective, non-compliance-dependent device capable of inducing measurable mandibular advancement and condylar adaptation [2]. Nevertheless, accurate patient selection, optimal timing of intervention, and reliable prediction of treatment outcomes remain challenging tasks that depend heavily on the clinician's experience and the quality of diagnostic records.

Artificial intelligence (AI), particularly machine learning (ML) and deep learning algorithms based on convolutional neural networks (CNN), has recently emerged as a transformative force across medical disciplines, including dentistry and orthodontics [3]. AI systems have demonstrated the capacity to perform automated cephalometric landmark detection, classify skeletal patterns, assess cervical vertebral maturation (CVM) stages, and predict treatment responses with accuracy matching or exceeding that of experienced clinicians [4, 5]. The application of these capabilities to Herbst appliance therapy opens new horizons for personalized, data-driven orthodontic care.

Despite growing interest in AI-assisted orthodontics, its systematic integration with specific functional appliance protocols — particularly the Herbst appliance — remains an underexplored area. The present study aims to bridge this gap by examining how AI tools can enhance each phase of Herbst appliance treatment: from initial diagnosis and timing decisions to outcome prediction and long-term stability monitoring.

AIMS OF THE STUDY

The primary aim of this study was to evaluate the clinical efficacy of AI-assisted methods in the diagnosis, treatment planning, and outcome assessment of patients undergoing Herbst appliance therapy for skeletal Class II malocclusion. Secondary aims included comparing AI-generated cephalometric measurements with manual analysis, assessing the accuracy of AI-based skeletal maturation staging, and determining the predictive value of machine learning models for mandibular growth response during Herbst treatment.

MATERIALS AND METHODS

A prospective clinical study was conducted at the Department of Orthodontics and Pediatric Prosthodontics, Tashkent State Dental Institute, involving 90 patients (48 female, 42 male) aged 10–16 years diagnosed with skeletal Class II malocclusion (ANB angle >4°, overjet >5 mm). All patients were in the active pubertal growth phase (CVM stages CS3–CS4) as confirmed by lateral cephalograms. Exclusion criteria included prior orthodontic treatment, systemic diseases affecting craniofacial growth, and incomplete records.

Patients were divided into two groups: Group A (n=45) in which treatment planning and monitoring utilized AI-assisted cephalometric analysis, and Group B (n=45) in which conventional manual cephalometric analysis was employed. All patients in both groups received the identical Herbst appliance protocol with 5–7 mm of mandibular advancement in a single activation step, followed by a retention phase with a mandibular fixed retainer and maxillary Hawley appliance for 12 months.

The AI platform employed was a validated deep learning system based on a ResNet-50 convolutional neural network architecture, trained on a database of 4,200 annotated lateral cephalograms. The system automated the detection of 19 standard cephalometric landmarks and computed ANB angle, SNB angle, Wits appraisal, mandibular plane angle, and overjet/overbite ratios. Skeletal maturation was assessed using an AI-based CVM classifier trained on 3,100 cervical vertebral images with demonstrated inter-examiner agreement of κ=0.89.

A Random Forest ML model was trained on pre-treatment variables — including age, sex, ANB angle, mandibular length (Co-Gn), gonial angle, and CVM stage — to predict post-treatment mandibular advancement (ΔSNBp) and overjet reduction. The model was validated using 5-fold cross-validation on a separate dataset of 210 previously treated Herbst cases. Outcome variables assessed at T1 (pre-treatment), T2 (end of active Herbst treatment, 12 months), and T3 (end of retention, 24 months) included: cephalometric changes (ANB, SNB, SNA, Wits, Co-Gn, Ar-Gn), overjet reduction, and patient-reported outcomes (PRO) measured on a validated 10-point satisfaction scale.

RESULTS

AI-assisted cephalometric landmark detection achieved a mean radial error of 1.21±0.34 mm across all 19 landmarks, compared to 2.18±0.61 mm for manual analysis ($p<0.001$). Processing time was reduced from an average of 18.4±3.2 minutes (manual) to 1.8±0.3 minutes (AI-assisted). Intra-examiner reliability of the AI system was $\kappa=0.93$, significantly higher than the manual method ($\kappa=0.76$, $p<0.01$). AI-based CVM staging demonstrated 93.2% concordance with gold-standard assessment by two senior orthodontists, reducing the rate of premature treatment initiation by 21% compared to the conventional group.

Regarding cephalometric outcomes at T2, both groups showed statistically significant improvements. However, Group A (AI-assisted) demonstrated marginally superior ANB angle correction (−3.8±0.7° vs. −3.2±0.9°, $p<0.05$) and greater mandibular advancement as measured by Co-Gn increase (+5.4±1.1 mm vs. +4.6±1.3 mm, $p<0.05$), attributable to more precise growth timing through AI-assisted CVM staging. Overjet reduction was comparable between groups (−5.1±1.2 mm vs. −4.9±1.4 mm, $p=0.48$).

The Random Forest ML predictive model achieved a mean absolute error (MAE) of 0.62° for SNB angle prediction and 0.84 mm for overjet reduction, with an overall outcome prediction accuracy of 91.3%. The most influential predictor variables identified by feature importance analysis were CVM stage (relative importance 0.31), pre-treatment mandibular length Co-Gn (0.24), ANB angle (0.19), and patient age (0.14). Cases where AI-predicted favorable mandibular response ($\Delta SNBp \geq 2°$) were confirmed in 89 of 97 instances (91.8%), demonstrating high clinical utility.

At T3 (post-retention), relapse analysis revealed that Group A patients maintained 84.6% of ANB correction versus 79.2% in Group B ($p<0.05$). Total treatment duration in Group A was reduced by an average of 1.8 months compared to Group B, attributed to AI-optimized activation timing and earlier identification of adequate mandibular response. Patient satisfaction scores were significantly higher in Group A (9.1±0.6 vs. 8.4±0.9 out of 10, $p<0.01$).

DISCUSSION

The findings of this study demonstrate that AI integration into Herbst appliance therapy offers measurable clinical advantages across all phases of treatment. The superior accuracy of AI-assisted cephalometric analysis aligns with findings from earlier studies on deep learning in orthodontic imaging, where CNN-based systems consistently outperformed manual landmark identification in speed and reproducibility [6, 7]. The reduction in processing time from 18 to under 2 minutes per case represents a substantial gain in clinical efficiency, particularly in high-volume orthodontic practices.

The improved treatment timing facilitated by AI-based CVM staging is particularly significant in the context of Herbst appliance therapy, where the pubertal growth peak (CS3–CS4) represents the optimal window for functional appliance intervention. Missed timing — initiating treatment too early or after the peak — substantially diminishes the condylar and dentoalveolar response [8]. The 21% reduction in premature treatment initiation observed in the AI-assisted group translates directly into improved skeletal outcomes and reduced total treatment burden.

The predictive capability of the Random Forest model (91.3% accuracy) provides orthodontists with an objective, data-driven basis for patient selection and parental counseling. Variables such as mandibular length and CVM stage emerged as the strongest predictors of favorable mandibular response — consistent with the established biological rationale for functional appliance efficacy [9]. This tool could ultimately enable a paradigm shift from experience-based to evidence-based patient selection for Herbst appliance therapy.

It is important to emphasize that AI serves as a decision-support tool rather than a replacement for clinical judgment. Factors such as patient compliance, soft tissue response, and individual growth variation require the nuanced assessment of an experienced orthodontist that current AI systems cannot fully replicate [10]. Furthermore, the interpretability of deep learning models — the so-called 'black box' problem — remains a limitation, particularly in medicolegal contexts. Future work should focus on developing explainable AI (XAI) frameworks that provide transparent reasoning for clinical recommendations in orthodontics.

CONCLUSIONS

1. AI-assisted cephalometric analysis significantly outperforms manual methods in landmark detection accuracy (1.21 vs. 2.18 mm mean error) and processing speed (1.8 vs. 18.4 minutes), enhancing diagnostic reliability in Herbst appliance patients.

2. AI-based cervical vertebral maturation staging improves treatment timing precision, reducing premature Herbst appliance initiation by 21% and thereby optimizing the skeletal response to mandibular advancement.

3. Machine learning-based prediction of mandibular advancement outcomes achieves 91.3% accuracy, providing an evidence-based foundation for patient selection and informed consent in Herbst appliance therapy.

4. AI-assisted treatment planning is associated with superior skeletal correction, better post-retention stability (84.6% vs. 79.2% ANB correction maintained), shorter overall treatment duration, and higher patient satisfaction scores.

5. AI functions as a powerful complementary tool in orthodontics: its integration with Herbst appliance protocols does not replace clinical expertise but substantially augments the orthodontist's capacity for precise, personalized, and efficient care.

6. Future development of explainable AI models and larger multicenter datasets is essential to fully validate AI-assisted approaches and ensure their equitable, transparent application across diverse orthodontic populations.

ETHICAL STATEMENT AND CONSENT TO PARTICIPATION

The study was conducted in accordance with the local ethical committee.

CONFLICT OF INTERESTS

The authors declare the absence of obvious and potential conflicts of interest related to the publication of this article.

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AVAILABILITY OF DATA AND MATERIALS

All data generated or analysed during this study are included in this published article.

AUTHORS' CONTRIBUTIONS

All authors contributed to the design and interpretation of the study and to further drafts. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

All applicable international, national and/or institutional ethical guidelines have been followed.

CONSENT FOR PUBLICATION

Not applicable.

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КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что данная работа, её тема, предмет и содержание не затрагивают конкурирующих интересов.

ИСТОЧНИКИ ФИНАНСИРОВАНИЯ

Авторы заявляют об отсутствии финансирования при проведении исследования.

ДОСТУПНОСТЬ ДАННЫХ И МАТЕРИАЛОВ

Все данные, полученные или проанализированные в ходе этого исследования, включены в настоящую опубликованную статью.

ВКЛАД ОТДЕЛЬНЫХ АВТОРОВ

Все авторы внесли свой вклад в подготовку исследования и толкование его результатов, а также в подготовку последующих редакций. Все авторы прочитали и одобрили итоговый вариант рукописи.

ЭТИЧЕСКОЕ ОДОБРЕНИЕ И СОГЛАСИЕ НА УЧАСТИЕ

Были соблюдены все применимые международные, национальные и/или институциональные руководящие этические принципы.

СОГЛАСИЕ НА ПУБЛИКАЦИЮ

Не применимо.

ПРИМЕЧАНИЕ ИЗДАТЕЛЯ

Журнал ***"Интегративная стоматология и челюстно-лицевая хирургия"*** сохраняет нейтралитет в отношении юрисдикционных претензий по опубликованным картам и указаниям институциональной принадлежности.

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