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RESEARCH

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Digital and artificial intelligence-assisted cephalometric training effectively enhanced students' landmarking accuracy in preclinical orthodontic education

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Abstract

Background Digital cephalometric analyses, including those assisted by artificial intelligence (AI), are widely used in clinical practice. Similarly, computer-assisted learning has demonstrated teaching outcomes comparable to those of traditional methods in orthodontic education. However, the potential application of digital and AI-assisted cephalometric training in the preclinical education of orthodontic students remains unexplored. Cephalometric analysis is a fundamental skill for orthodontic students and practitioners. Therefore, this study aimed to integrate digital and AI-assisted cephalometric training into preclinical orthodontic education and evaluate its educational effectiveness.

Methods Forty undergraduate students were grouped into pairs to use digital cephalometric training software. The students' landmarking abilities were evaluated by comparing their total scores before and after training on the same two lateral radiographs using digital cephalometric training software. The effectiveness of the software in improving landmarking accuracy was assessed objectively. Lateral radiographs of eight common patient types were selected. Twenty-four clinical training students from different grades used an AI-assisted cephalometric platform to analyze skeletal, dental, and soft tissue indicators. The accuracy of the measurements was compared among students in different grades.

Results Digital cephalometric training, through real-time feedback and visual error-correction mechanisms, enabled students to quickly identify and correct errors in landmarking, significantly improving their accuracy. There was no significant difference in AI-assisted cephalometric analysis ability among students with varying levels of clinical experience.

Conclusions Digital cephalometric training effectively enhances students' landmarking accuracy in preclinical orthodontic education. AI-assisted cephalometry has the potential to minimize performance disparities among students with varying levels of clinical experience. Owing to the real-time feedback and self-directed learning features of digital tools, these technologies serve as valuable supplements to instructor-led training, potentially reducing

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educators' workload and accelerating skill acquisition in novice orthodontic students. However, these preliminary findings require further multicenter validation and long-term educational assessments while also considering the ethical implications of these technologies.

Keywords Digital technology, Computer-assisted learning, Preclinical education, Orthodontic care, Artificial intelligence

Introduction

The application of digital technology (DT) in modern dentistry has become increasingly widespread, significantly affecting various aspects, including patient diagnosis, prosthetic design, clinical crown preparation, and the exchange and storage of patient data [1]. Implementing DT enhances communication efficiency and treatment quality and substantially improves patient experience [2]. However, traditional teaching methods remain dominant in dental education, posing challenges to the widespread adoption of digital learning [3]. High-quality digital training is crucial for producing graduates with advanced technical competencies [2]. Therefore, integrating DT into dental education, particularly through promoting and applying computer-assisted learning (CAL), is vital for enhancing educational quality.

With the rapid advancement of DT, its application in orthodontics has gradually become widespread and is emerging as a mainstream trend in professional development [4]. DT is now extensively used at various stages, including malocclusion analysis, treatment planning, and the production of orthodontic appliances [5]. Technologies such as 3D scanning and 3D printing have enabled the creation of personalized invisible aligners and customized archwires. Visualizing orthodontic treatment plans has significantly improved communication between clinicians and patients, reducing procedure time [6]. In particular, using artificial intelligence (AI) in dentistry has significantly improved dental imaging and orthodontics [7]. AI applications in orthodontics span several areas, including assessing bone age, performing cephalometric analysis, automatically segmenting cone-beam computed tomography (CBCT) images, and analyzing big data on tooth movement in treatment design [8].

CAL has proven to be as effective as traditional learning methods in orthodontic education related to diagnosis and treatment planning [9]. Additionally, integrating DT into graduate education significantly enhances students' learning satisfaction [6]. Research has investigated the effectiveness of digital software in teaching cephalometric measurements, with findings indicating favorable outcomes and high acceptance [10]. However, despite the widespread clinical use of digital cephalometry, including AI-assisted cephalometric analysis [8], no studies have explored its potential application in preclinical education for orthodontic students.

Digital cephalometric analysis is essential for orthodontic students and practitioners. Therefore, exploring the application of digital cephalometric analysis and AI-assisted cephalometric teaching in preclinical orthodontic education can overcome the limitations of traditional teaching methods while effectively cultivating students' digital diagnostic skills. This study aimed to integrate digital cephalometric analysis into preclinical orthodontic education, systematically and objectively evaluate students' learning outcomes using a digital teaching and assessment platform, and advocate for its broader adoption in educational and clinical settings.

Methods

Digital cephalometric training

The instructor began by using a PowerPoint (Microsoft, WA, USA) presentation to explain the landmark points for various cephalometric analysis methods, detailing the clinical significance and precise positioning of each landmark. Subsequently, the students were trained using digital cephalometric software (Uceph, Chengdu, China). Specifically, the training software included preloaded lateral radiographs with predefined "correct positions" for various landmark points. The students used lateral radiographs A and B (Fig. 1) for the test. When a student clicked on a landmark, the system assigned a score based on the distance between the selected point and its "correct position," with a score range of 0–10, wherein closer proximity to the correct position led to a higher score. After completing all the landmarks, the system automatically generated a total score for the radiograph, representing the student's initial landmarking ability.

The training function of the head-shadow measurement software was then activated. When locating different marking points on lateral radiograph C, the software visually indicated the "correct position" using a circle around the landmark. Students could adjust their landmarks until they were close to the "correct answer." Once the training was completed, the students reassessed their skills by relabeling lateral radiographs A and B, and a new total score was generated (Fig. 2). Forty undergraduate students from the School of Stomatology at Southern Medical University were divided into pairs for cephalometric landmarking. Each pair measured two lateral radiographs, and the total scores for landmark identification before and after training were recorded. By comparing the total scores before and after training, the

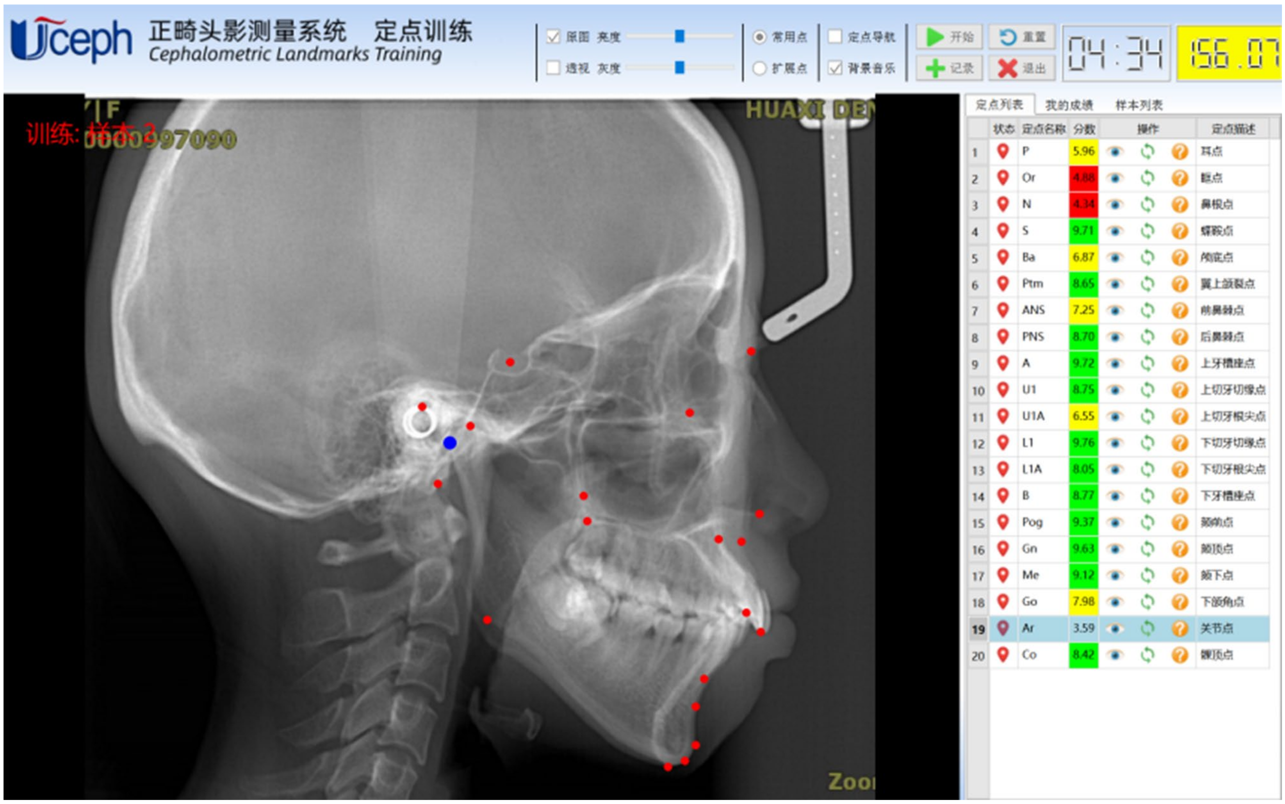

Fig. 1 The students' landmarking score was recorded before the Cephalometric Landmarks Training

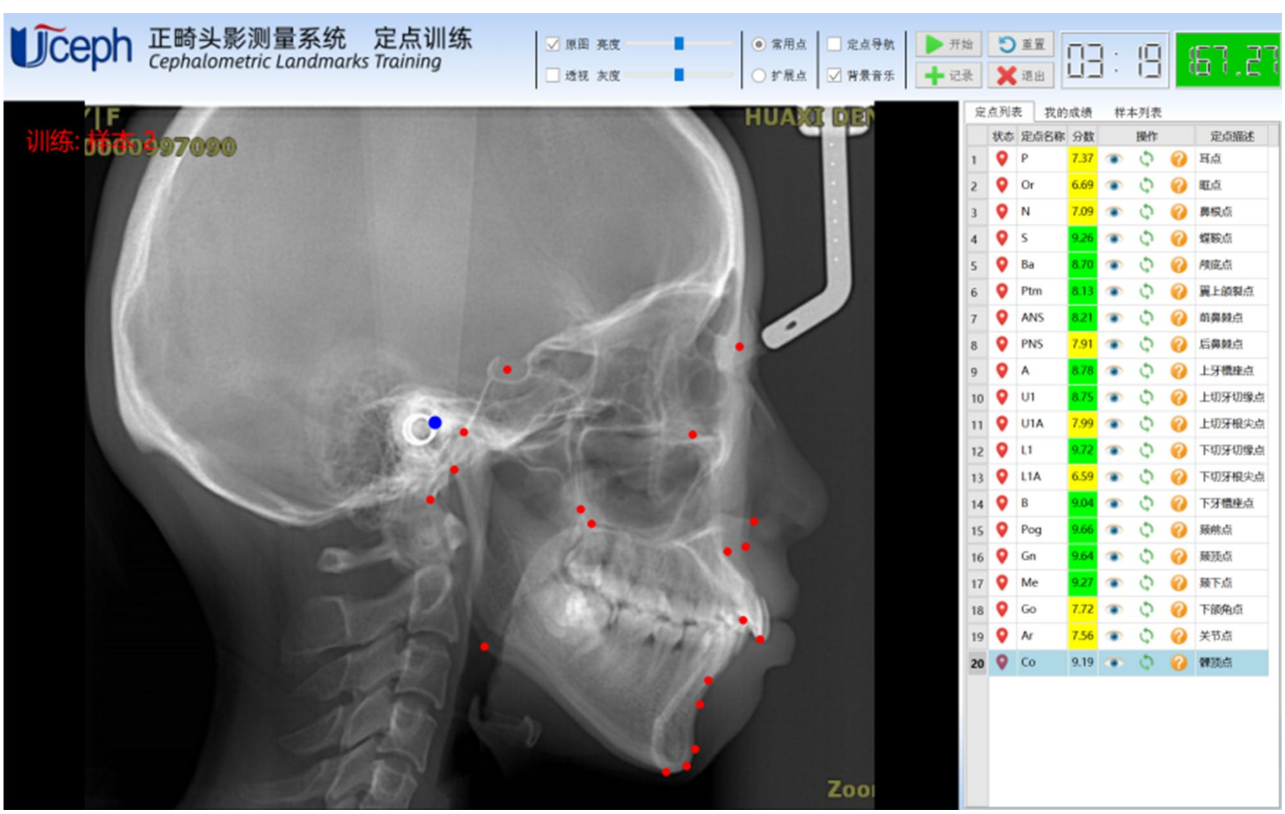

Fig. 2 The students' landmarking score was recorded after the Cephalometric Landmarks Training

effectiveness of the digital cephalometric training software in improving students' landmarking abilities was objectively evaluated.

AI-assisted cephalometric training

Lateral radiographs of patients receiving orthodontic treatment at Southern Medical University Dental Hospital in 2024 were collected. Based on the experience and recommendations of senior practitioners, patients were selected according to the following diagnoses: crowding, spacing, class III malocclusion, deep overbite, class II malocclusion, open bite, deep bite, bimaxillary protrusion, and crossbite. One patient was included for each diagnosis. The instructor first explained the operation of the AI-assisted cephalometric platform (Linkedcare, Shanghai, China) to the students, including how to locate landmarks, modify the landmark positions, and access measurement data for various cephalometric analysis methods. During the cephalometric analysis phase, 24 students undergoing clinical training at the Stomatology Hospital of Southern Medical University were divided into three groups based on their year of training (first, second, and third grade). Students from different grades used the AI-assisted automatic landmark recognition feature to identify cephalometric landmarks on lateral radiographs of eight classic cases. The system provided an initial set of automatically identified landmark positions, which students reviewed and adjusted based on their judgment (Fig. 3). Upon completion, a comprehensive analysis of skeletal, dental, and soft tissue indicators was performed and the results were recorded using a questionnaire, which was designed with standard score values for all answers (the questionnaire is provided in the Supplementary Material). After submission, the system automatically generated specific scores for each case. By comparing these scores, the accuracy of the measurements obtained through the AI-assisted cephalometric analysis was evaluated for students of different grades.

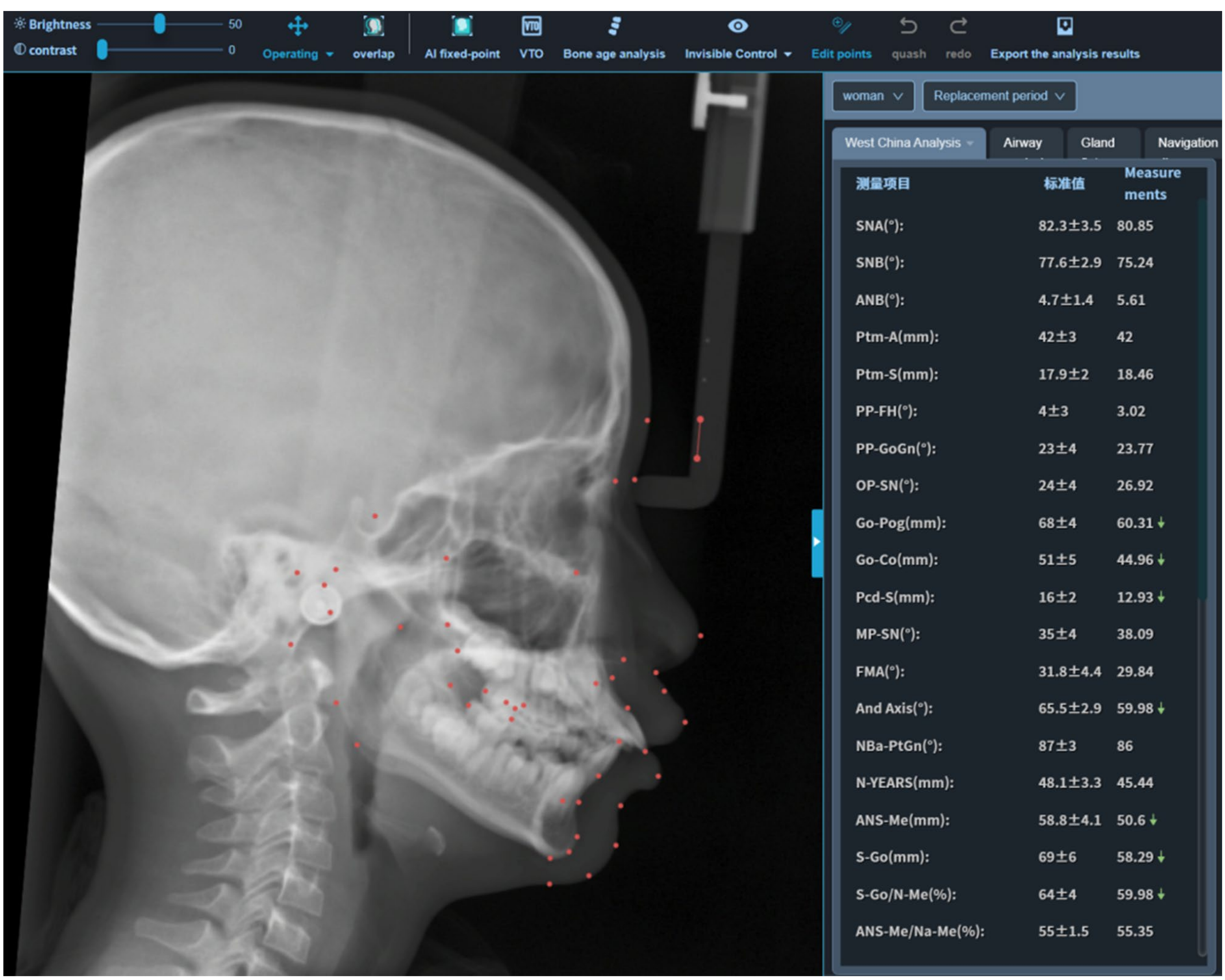

Fig. 3 AI-assisted cephalometric landmarking platform

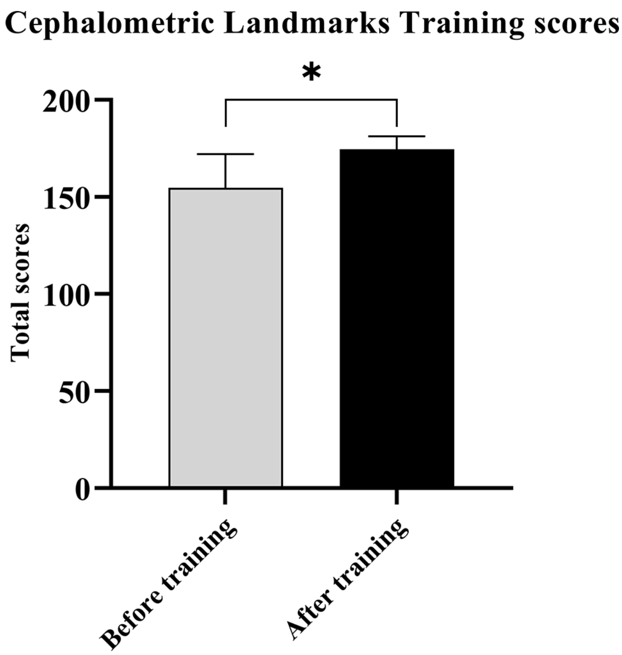

Fig. 4 Cephalometric landmarks training scores

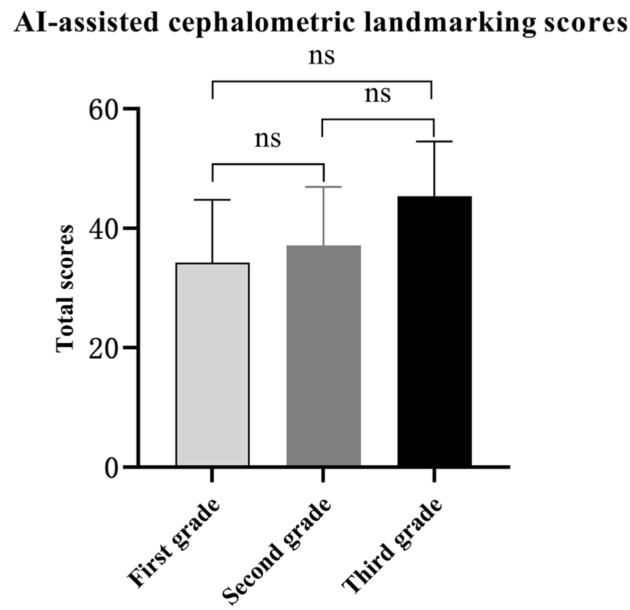

Fig. 5 AI-assisted cephalometric landmarking scores

Statistical analysis

Statistics were calculated using SPSS 20.0 (IBM, Armonk, NY, USA) software. All the data are represented as mean ± standard deviation. Group comparisons were conducted using the paired t-test or one-way analysis of variance. Since multiple comparisons were not involved in this study, the significance level (α) was set at 0.05. A *p*-value of less than 0.05 is considered statistically significant.

Results

Digital cephalometric training significantly improves landmarking skills

The application of digital cephalometric landmark training in preclinical orthodontic education has not been previously explored. This study examined the use of digital cephalometric landmark training in preclinical orthodontic education to assess its effectiveness in enhancing students' landmarking skills. CAL, which provides real-time feedback and error correction, was used for this purpose. Students initially performed digital landmarking, followed by practice sessions using digital software that provided real-time prompts to correct the "accurate position" of landmarks. After completing the training, the students underwent reassessment, and their pre- and post-training scores were compared. The findings indicated that the average total score before training was 154.7, which significantly increased to 174.6 after training (Fig. 4). This improvement was statistically significant ($p < 0.001$) and demonstrated that digital cephalometric training effectively and efficiently enhanced the students' landmarking abilities.

These findings highlight the potential of digital training methods in orthodontic education. By providing real-time feedback and a visual error correction mechanism, these methods enabled students to quickly identify and address deficiencies in their landmarking processes, potentially reducing educators' workload and accelerating skill acquisition in novice orthodontic students. Future research should explore the application of digital training across various educational stages and teaching contexts to evaluate its long-term effectiveness and applicability.

AI-assisted cephalometric landmarking reduces technical sensitivity

The application of AI-assisted cephalometric analysis in preclinical orthodontic education remains underexplored. This study utilized AI-assisted cephalometric analysis to perform landmarking on lateral radiographs of common clinical case types and evaluated differences in diagnostic accuracy for skeletal, dental, and soft tissue indicators among students of different grades using the AI landmarking tool.

As illustrated in Fig. 5, the findings revealed that although the average score of advanced students was slightly higher, the differences between the three groups were not statistically significant ($p > 0.05$). Introducing DT, particularly the application of AI assistance, reduced subjective errors in diagnostic analysis and lowered technical sensitivity (minimizing the variation in cephalometric analysis proficiency among operators with varying levels of clinical experience). Given the limitations of the sample size, the results of AI-assisted cephalometric training should be interpreted with caution. The students' primary task was to verify and adjust the landmarking results generated by AI, rather than starting from scratch, to identify and measure complex landmarks. This streamlined process simplified the analysis workflow, enabling students of different grades to achieve relatively accurate diagnoses, regardless of their clinical experience.

These findings suggest that AI-assisted cephalometry has the potential to reduce the skill gap between students with varying levels of expertise. This highlights the value of DT in helping beginners quickly acquire diagnostic proficiency.

Discussion

This study aimed to integrate digital cephalometric analysis into preclinical orthodontic education and systematically evaluate student learning outcomes using a digital teaching and assessment platform. The findings demonstrated that digital cephalometric training significantly and rapidly improved students' landmark accuracy. In the AI-assisted cephalometric analysis, there was no significant difference in the accuracy of students in different grades, which highlights the positive application value of digital cephalometric training and AI-assisted cephalometric measurement in the preclinical education of orthodontic students.

Conventional preclinical cephalometric training involves several steps. First, instructors presented theoretical concepts through slide-based lectures. Subsequently, they conducted landmarking exercises using either prerecorded videos or live demonstrations on specially prepared paper templates [11]. Students then practiced independently, and their assignments were graded by the instructor. This traditional approach is widely employed in many dental education institutions and has been proven effective in preclinical training [12]. However, this method has certain significant limitations. First, traditional training requires substantial human resources and a single instructor is often responsible for supervising multiple students. Additionally, the grading process requires considerable time, which further increases the teaching workload. Second, traditional assessment methods often lack objectivity and consistency. Because grading relies on an instructor's personal judgment, significant variability may occur in the evaluation of the same task by different instructors [12]. This variability is influenced by factors such as instructor experience, evaluation criteria, and subjective biases [3]. Studies have revealed that internal consistency of the traditional evaluation methods does not reach the minimum acceptable standard. Additionally, the consistency between the raters is significantly lower than the internal consistency of the raters. Even the same instructor may assign inconsistent grades to the same assignment at different times [13]. Lastly, owing to limited teaching time, instructors often struggle to provide timely and detailed feedback on each student's work. This lack of feedback can leave students without clear guidance for improvement and may lead to disagreements between students and instructors regarding grading outcomes [12]. Without real-time feedback, students frequently struggle to identify their deficiencies during landmarking exercises and are unable to adjust their techniques promptly, which can adversely impact their learning outcomes.

Image quality issues affect the judgment of orthodontists who lack experience in cephalometric analysis. In contrast, fully automated software significantly reduces the errors caused by subjective bias during landmark identification [14]. Additionally, digital software improves image clarity by dynamically adjusting the grayscale and contrast of radiographs, making details that are difficult to discern on printed paper more visible [10]. Automated measurement can improve work efficiency; the required time is only half that time of manual landmarking [15]. Studies have revealed that digital automatic measurement methods are more efficient and less time-consuming, while offering accuracy comparable to or better than manual methods [10]. However, research has shown that AI-automated cephalometric tracing can be slower and less accurate than human operators with respect to specific measurements, suggesting that its reliability varies depending on the context and variables assessed [16]. This underscores the importance of training students to critically evaluate AI output, as demonstrated in our study. Furthermore, digital systems enable students to engage in repeated practice until the desired proficiency is achieved. The inclusion of real-time feedback minimizes the need for one-on-one instruction and fosters self-directed learning among students. Digital teaching methods can enhance student learning efficiency and effectively reduce the workload of educators [17], aligning with the findings of our study. It was observed that due to the immediate feedback capability of digital tools and their support for independent learning, students' performance in landmark identification tasks improved rapidly, potentially alleviating teachers' workload. This underscores the value of digital tools in modern orthodontic education.

Studies indicate that digital intraoral scanning allows students with limited clinical experience to produce models of comparable quality to those created using traditional alginate impressions. These findings highlight the potential value of introducing DT early in dental hygiene education [18]. Our study demonstrated that digital cephalometric analysis significantly reduced landmarking errors among students in different grades. Both advanced and junior students can make relatively accurate diagnoses using this technology. These findings suggest that digital systems reduce technical sensitivity, allowing inexperienced students and less experienced orthodontists to achieve relatively precise measurements with AI assistance. This highlights the potential of DT to support beginners in rapidly gaining proficiency. Such advantages not only enhance educational outcomes but also allow orthodontic students and early-career practitioners to allocate more time to treatment planning and monitoring, thereby improving treatment efficiency. Additionally, owing to the superior image analysis accuracy of AI compared to that of less experienced dental practitioners [19], AI-assisted teledentistry enables easy sharing of patient data, remote monitoring of orthodontic treatment progress, evaluation of treatment outcomes, and timely provision of consultation [5, 20]. Our findings suggest that digital teaching methods support novice orthodontic students in rapidly improving their cephalometric skills, with potential clinical value in remote dental consultations.

Given the numerous advantages of digital analysis platforms, the feasibility of adopting online digital education and remote learning in orthodontic courses warrants further investigation. Currently, most dental training institutions employ teacher-centered instructional models. However, traditional teaching methods often encourage rote memorization, resulting in suboptimal learning outcomes [21]. During the coronavirus disease 2019 pandemic, many dental training institutions experimented with online teaching formats. Although the number of participants in online dental prosthodontics courses has significantly increased, studies have revealed lower student progress and course completion rates [22]. The correlation between remote learning and poor academic performance has raised concerns among academics and educational regulators regarding the quality of remote education [23]. Studies indicate that while both students and instructors exhibit a high level of acceptance of online teaching models, traditional foundational dental education remains a cornerstone of the curriculum [24]. Balancing the proportion of online digital education with hands-on practical training has therefore become a critical challenge in dental education. A consensus among many studies suggests that combining traditional methods with CAL is more effective in enhancing dental skills [25]. Specifically, educators are encouraged to adopt a hybrid teaching strategy: face-to-face instruction should be prioritized for the development of practical skills, while theoretical content can be delivered through remote education [26]. This leverages the strengths of traditional teaching while taking full advantage of the convenience and flexibility of digital education. It provides students with a more comprehensive learning experience, ultimately enhancing their overall competence in dental practice.

From the instructors' perspective, while DT offers convenience to students, it may lead to a lack of deep understanding of key concepts, such as the definitions of measurements and their clinical significance. In contrast, traditional measurement methods not only enhance students' hands-on skills but also reinforce their retention of relevant knowledge [10]. Additionally, some educators have expressed concerns about the high initial costs associated with creating digital learning materials, which remain a significant barrier to the widespread adoption of digital teaching methods [27]. From the students' perspective, they generally recognize the advantages of AI tools in terms of diagnostic speed, objectivity, and reducing misdiagnosis rates. They also acknowledge the indispensable role of AI tools in dental practice and advocate the inclusion of AI-related courses in dental education [28, 29]. However, students disagree with the idea that AI can replace dentists and prefer that instructors assess their technical skills [3, 30]. Students value recording lectures and clinical procedures, acknowledging that personalized guidance and feedback from instructors cannot be entirely replaced by digital simulators. Instructors are responsible for imparting knowledge and skills, playing a crucial role in transmitting experiential insights and serving as professional role models through their clinical expertise and behavior. This direct guidance and influence is essential for students' development, underscoring the significant responsibility educators bear in shaping the next generation of dentists [31]. Most students acknowledge that traditional teaching methods remain indispensable for cultivating critical thinking and self-assessment skills. These abilities are fundamental to the educational process and are essential for the effective application of knowledge in daily clinical practice. Relying solely on DT may not adequately fulfill these needs [13]; therefore, a teaching approach combining DT with traditional methods is essential. This model balances the convenience of technology with the depth of traditional instruction, providing students with a comprehensive and well-rounded learning experience.

AI tools have limitations. On one hand, their accuracy is influenced by factors such as the choice of AI model, the clarity of radiographs, and the quality of training data, which can compromise diagnostic precision and potentially pose a risk to patient safety [32]. On the other hand, the integration of AI in dentistry continues to raise ethical concerns related to patient privacy and data security [19]. These limitations highlight the need for continued research to optimize the application of digital tools in both education and clinical practice. Despite these issues, a North American study revealed that 56.1% of orthodontic program directors had already implemented or planned to integrate AI-related teaching into their curricula [33]. Researchers generally agree that human expertise remains irreplaceable, particularly in areas such as empathy, ethical considerations, and the ability to interpret complex information that AI may not fully understand [28]. The current consensus is that AI will serve as a complementary tool to clinical expertise and skills, rather than a replacement [19].

This study included student cohorts spanning different educational levels, from undergraduate preclinical stages to postgraduate clinical practice, which significantly enhanced the diversity and reliability of the findings. To our knowledge, this is the first study to explore the application of digital cephalometric landmarking training, and AI-assisted cephalometric analysis in preclinical education. We aimed to advance and refine orthodontic education through digital innovations that align with contemporary developments, and offer a modernized teaching model for orthodontic training. This study had some limitations. First, considering that we only collected data from currently enrolled clinical training students, the sample size was relatively small. As a result, the findings from AI-assisted cephalometric training may lack statistical power. Therefore, the results should be interpreted with caution, and the sample size should be increased in future studies to enhance the representativeness and generalizability of the findings. Second, the lack of strict requirements for student measurement time may have led to performance bias among individual students, including cases of underachievement or overachievement, potentially affecting the accuracy of the findings. Third, the study provides limited insight into students' attitudes toward the integration of digital technologies into the curriculum, failing to fully assess their acceptance of these tools and their impacts on learning outcomes. This may partially hinder a comprehensive evaluation of the advantages and disadvantages of digital technologies in orthodontic education. Future plans include exploring a hybrid model that combines AI-generated feedback with personalized instructor guidance. Multicenter validation will be conducted to assess the generalizability of the findings. A long-term educational outcome evaluation framework will be designed to track student progress and assess skill retention and clinical translation during clinical internships. Emphasis will be placed on ensuring that students have a solid understanding of the ethical considerations related to digital technologies and AI, ensuring their safe and responsible use.

Conclusion

Digital cephalometric training effectively enhances students' landmarking accuracy in preclinical orthodontic education. AI-assisted cephalometric has the potential to minimize performance disparities among students with varying levels of clinical experience. Owing to the real-time feedback and self-directed learning features of digital tools, these technologies serve as a valuable supplement to instructor-led training, potentially reducing educators' workload and accelerating skill acquisition in novice orthodontic students. This highlights the positive application value of digital cephalometric training and AI-assisted cephalometric measurement in the preclinical education of orthodontic students. However, these preliminary findings require further multicenter validation and long-term educational assessments while also considering the ethical implications of these technologies.

Abbreviations

AI	Artificial intelligence
DT	Digital technology
CAL	Computer-assisted learning
CBCT	Cone-beam computed tomography

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12903-025-05978-4.

Supplementary Material 1

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Author contributions

J.L. performed the experiments and did the manuscript writing. Z.L. and J.D. performed the experiments and did the manuscript writing. M.W. and R.Y. did the data collection. H.Y. carried out statistical analysis. C.L. conceived and supervised the whole project. All authors read and approved the final manuscript.

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Data availability

The data underlying this article will be shared on reasonable request by the corresponding author.

Declarations

Ethics approval and consent to participate

This study was approved by the Ethical Committee of the Department of the Affiliated Hospital of Stomatology, Southern Medical University (Approval No.2022-37). The methods were carried out in accordance with relevant guidelines and regulations. All data used in this study were collected for diagnosis and analysis and Informed consent has been obtained from all participants.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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References

1. Ishida Y, Kuwajima Y, Kobayashi T, Yonezawa Y, Asack D, Nagai M, Kondo H, Ishikawa-Nagai S, Silva JD, Lee SJ. Current implementation of digital dentistry for removable prosthodontics in US dental schools. Int J Dent. 2022;2022:7331185. https://doi.org/10.1155/2022/7331185.
2. Alnafaiy SM, Alyousef H, Aljabr R, Tounsi A, Almutairi R, Albaijan RS. Digital technology implementation in prosthodontics postgraduate programs in Saudi Arabia: a multi-institutional survey of program directors. BMC Oral Health. 2024;24:1136. https://doi.org/10.1186/s12903-024-04908-0.
3. Schlenz MA, Michel K, Wegner K, Schmidt A, Rehmann P, Wostmann B. Undergraduate dental students' perspective on the implementation of digital dentistry in the preclinical curriculum: a questionnaire survey. BMC Oral Health. 2020;20:78. https://doi.org/10.1186/s12903-020-01071-0.
4. Jacox LA, Bocklage C, Edwards T, Mihas P, Lin FC, Ko CC. Understanding technology adoption by orthodontists: a quantitative study. Am J Orthod Dentofac. 2022;161:364–74. https://doi.org/10.1016/j.ajodo.2020.08.024.
5. Pandey R, Kamble R, Kanani H. Revolutionizing smiles: advancing orthodontics through digital innovation. Cureus. 2024;16:e64086. https://doi.org/10.7759/cureus.64086.
6. Allanqawi T, Alkadhimi A, Fleming PS. Postgraduate orthodontic education: an international perspective on content and satisfaction levels. J World Fed Orthod. 2023;12:239–44. https://doi.org/10.1016/j.ejwf.2023.08.004.
7. Thurzo A, Urbanova W, Novak B, Czako L, Siebert T, Stano P, Marekova S, Fountoulaki G, Kosnacova H, Varga I. Where is the artificial intelligence applied in dentistry? Systematic review and literature analysis. Healthcare. 2022;10(7):1269. https://doi.org/10.3390/healthcare10071269.
8. Surlari Z, Budala DG, Lupu CI, Stelea CG, Butnaru OM, Luchian I. Current progress and challenges of using artificial intelligence in clinical dentistry: a narrative review. J Clin Med. 2023;12(23):7378. https://doi.org/10.3390/jcm12237378.
9. Al-Jewair TS, Azarpazhooh A, Suri S, Shah PS. Computer-assisted learning in orthodontic education: a systematic review and meta-analysis. J Dent Educ. 2009;73:730–39.
10. Yu X, Tian Y, Li D, Sun W, Wang H, Yuan S, Yan B, Wang L, Pan Y. Evaluating the effect of digital technology on the learning of orthodontic cephalometric measurement. F1000Res. 2022;11:328. https://doi.org/10.12688/f1000research.109876.2.
11. Drage NA, Atkin PA, Farnell D. Dental and maxillofacial radiology: confidence, knowledge and skills in the newly graduated dentist. Br Dent J. 2020;228:546–50. https://doi.org/10.1038/s41415-020-1425-x.
12. Yu W, Zhu Z, Su T, Weng W, Xu C. A pilot study on the use of a novel digital real-time evaluation system in undergraduate preclinical training of tooth Preparation in fixed prosthodontics. Eur J Dent Educ. 2023;27:949–55. https://doi.org/10.1111/eje.12886.
13. Yamakami SA, Nagai M, Chutinan S, Ohyama H. 3D digital technology as an alternative educational tool in preclinical dentistry. Eur J Dent Educ. 2022;26:733–40. https://doi.org/10.1111/eje.12755.
14. Ye H, Cheng Z, Ungvijanpunya N, Chen W, Cao L, Gou Y. Is automatic cephalometric software using artificial intelligence better than orthodontist experts in landmark identification? BMC Oral Health. 2023;23:467. https://doi.org/10.1186/s12903-023-03188-4.
15. Chen SK, Chen YJ, Yao CC, Chang HF. Enhanced speed and precision of measurement in a computer-assisted digital cephalometric analysis system. Angle Orthod. 2004;74:501–07. https://doi.org/10.1043/0003-3219(2004)074%3C0501:ESAPOM%3E2.0.CO;2.
16. Strunga M, Ballova DS, Tomasik J, Oravcova L, Danisovic L, Thurzo A. AI-automated cephalometric tracing: a new normal in orthodontics? 2024 International Conference on Artificial Intelligence, Computer, Data Sciences and Applications (ACDSA). https://doi.org/10.1109/ACDSA59508.2024.10467825
17. Sipiyaruk K, Kaewsirirat P, Santiwong P. Technology-enhanced simulation-based learning in orthodontic education: a scoping review. Dent Press J Orthod. 2023;28:e2321354. https://doi.org/10.1590/2177-6709.28.3.e2321354.oar.
18. Naderi RK, Patel TJ, Thompson MA. A comparison study: the use of digital and conventional impression techniques in dental hygiene education. J Dent Educ. 2024;88:518–23. https://doi.org/10.1002/jdd.13467.
19. Tuygunov N, Samaranayake L, Khurshid Z, Rewthamrongsris P, Schwendicke F, Osathanon T, Yahya NA. The transformative role of artificial intelligence in dentistry: a comprehensive overview part 2: the promise and perils, and the international dental federation communique. Int Dent J. 2025;75:397–404. https://doi.org/10.1016/j.identj.2025.02.006.
20. Batra P, Tagra H, Katyal S. Artificial intelligence in teledentistry. Discoveries (Craiova). 2022;10:153. https://doi.org/10.15190/d.2022.12.
21. Chen D, Zhao W, Ren L, Tao K, Li M, Su B, Liu Y, Ban C, Wu Q. Digital PBL-CBL teaching method improves students' performance in learning complex implant cases in atrophic anterior maxilla. PeerJ. 2023;11:e16496. https://doi.org/10.7717/peerj.16496.
22. Yang X, Li D, Liu X, Tan J. Learner behaviors in synchronous online prosthodontic education during the 2020 COVID-19 pandemic. J Prosthet Dent. 2021;126:653–57. https://doi.org/10.1016/j.prosdent.2020.08.004.
23. Silva P, Dias CC, Machado LC, Carlos A, Dantas TS, Ximenes J, Sousa R, Sousa FB. Distance education in dentistry in Brazil: a critical STROBE-based analysis. Braz Oral Res. 2021;35:e109. https://doi.org/10.1590/1807-3107bor-2021.vol35.0109.
24. Schlenz MA, Wostmann B, Kramer N, Schulz-Weidner N. Update of students' and lecturers' perspectives on online learning in dental education after a five-semester experience due to the SARS-CoV-2 (COVID-19) pandemic: insights for future curriculum reform. BMC Med Educ. 2023;23:556. https://doi.org/10.1186/s12909-023-04544-2.
25. Gredes T, Pricop-Jeckstadt M, Mereti E, Botzenhart U. Survey of student attitudes toward digital technology in practical technical dental education using the AR-Demonstrator-App. J Dent Educ. 2022;86:12–20. https://doi.org/10.1002/jdd.12783.
26. Johnson KO, Ryan F, Cunningham S. Postgraduate student perceptions of face-to-face and distance education in orthodontics: a cross-sectional qualitative study. J Orthod. 2022;49:280–87. https://doi.org/10.1177/14653125221077108.
27. Park JC, Kwon HE, Chung CW. Innovative digital tools for new trends in teaching and assessment methods in medical and dental education. J Educ Eval Health Prof. 2021;18:13. https://doi.org/10.3352/jeehp.2021.18.13.
28. Yilmaz C, Erdem RZ, Uygun LA. Artificial intelligence knowledge, attitudes and application perspectives of undergraduate and specialty students of faculty of dentistry in Turkey: an online survey research. BMC Med Educ. 2024;24:1149. https://doi.org/10.1186/s12909-024-06106-6.
29. Gupta S, Verma S, Chauhan AK, Roy MS, Rajkumari W, Sahgal C. Knowledge, attitude, and perception of orthodontic students, and orthodontists regarding role of artificial intelligence in field of orthodontics: an online cross-sectional survey. J World Fed Orthod. 2025;14:3–11. https://doi.org/10.1016/j.ejwf.2024.08.002.
30. Ozbey F, Yasa Y. The relationships of personality traits on perceptions and attitudes of dentistry students towards AI. BMC Med Educ. 2025;25:26. https://doi.org/10.1186/s12909-024-06630-5.
31. Zitzmann NU, Matthisson L, Ohla H, Joda T. Digital undergraduate education in dentistry: a systematic review. Int J Environ Res Public Health. 2020;17(9):3269. https://doi.org/10.3390/ijerph17093269.
32. Lin L, Tang B, Cao L, Yan J, Zhao T, Hua F, He H. The knowledge, experience, and attitude on artificial intelligence-assisted cephalometric analysis: survey of orthodontists and orthodontic students. Am J Orthod Dentofac. 2023;164:e97–105. https://doi.org/10.1016/j.ajodo.2023.07.006.

33. Hanenkrath J, Park JH, Bay C. Training, use, and modifications related to artificial intelligence in postgraduate orthodontic programs in North America. Am J Orthod Dentofac. 2025;167:89–94. https://doi.org/10.1016/j.ajodo.2024.09.008.

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