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ORIGINAL

Development of a semi-automatic collaborative system for cephalometric measurement in orthodontic radiographic images

Desarrollo de un sistema colaborativo semiautomático para la medición cefalométrica en imágenes radiográficas ortodóncicas

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ABSTRACT

Cephalometric analysis is a fundamental tool in orthodontics for evaluating craniofacial morphology using radiographic images. However, traditional manual methods are time-consuming and show inter-observer variability, while fully automated artificial intelligence systems still face limitations in clinical reliability and generalization. This study presents a collaborative semi-automatic system designed to improve efficiency and consistency in two-dimensional cephalometric analysis. The system integrates digital templates with expert-assisted landmark identification, allowing trained users to mark anatomical reference points while the software automatically performs geometric calculations. A comparative evaluation was conducted between the manual and semi-automatic methods, focusing on processing time, landmark localization accuracy, and operational workload. The results showed a significant reduction in average processing time per radiograph, decreasing from 12.5 minutes using the manual method to 4.3 minutes with the proposed system. In addition, a decrease in variability in landmark identification was observed, particularly in mandibular structures where manual measurements tend to be less consistent. The semi-automatic approach also reduced workload by automating calculation and data recording processes while maintaining expert control during the marking phase. It is concluded that the combination of clinical expertise and computational support improves both efficiency and consistency in orthodontic analysis.

Keywords: Cephalometric analysis; Orthodontics; Semi-automatic system; Craniofacial measurement.

RESUMEN

El análisis cefalométrico es una herramienta fundamental en ortodoncia para la evaluación de la morfología craneofacial mediante imágenes radiográficas. Sin embargo, los métodos manuales tradicionales son lentos y presentan variabilidad entre observadores, mientras que los sistemas totalmente automatizados basados en inteligencia artificial aún enfrentan limitaciones en su confiabilidad clínica y generalización. Este estudio presenta un sistema colaborativo semiautomático diseñado para mejorar la eficiencia y consistencia en el análisis cefalométrico bidimensional. El sistema integra plantillas digitales con la intervención de expertos para la identificación de puntos anatómicos, permitiendo que el usuario especializado marque los landmarks mientras el software realiza automáticamente los cálculos geométricos. Se realizó una evaluación comparativa entre el método manual y el semiautomático, considerando el tiempo de procesamiento, la precisión en la localización de puntos y la carga operativa. Los resultados mostraron una reducción significativa del tiempo promedio por radiografía, pasando de 12.5 minutos en el método manual a 4.3 minutos con el sistema propuesto. Además, se observó una disminución de la variabilidad en la identificación de landmarks, especialmente en estructuras mandibulares. El enfoque semiautomático también redujo la carga de trabajo al automatizar cálculos y registro de datos, manteniendo el control experto en la fase de marcación. Se concluye que la combinación de conocimiento clínico y soporte computacional mejora la eficiencia y consistencia del análisis ortodóncico.

Palabras clave: Análisis cefalométrico; Ortodoncia; Sistema semiautomático; Medición craneofacial.

INTRODUCTION

The morphological evaluation of the craniofacial complex has historically been a fundamental pillar in clinical orthodontics and biomedical research, particularly through the use of cephalometric analysis based on lateral radiographic images. Since the pioneering work of Broadbent (1931), who introduced an innovative radiographic technique for the orthodontic study of the skull, the methodological foundation was established for quantifying skeletal and dentofacial relationships in two dimensions. This approach enabled the development of numerous longitudinal studies aimed at understanding craniofacial growth patterns and variation in different populations (Yamaguchi et al., 2001; Lim et al., 2013).

However, the accuracy of measurements obtained from two-dimensional images has been widely debated due to inherent limitations such as the superimposition of anatomical structures and the lack of depth information. In this context, the introduction of cone-beam computed tomography (CBCT) has represented a significant advance, enabling more precise and reliable three-dimensional reconstructions for the identification of cephalometric landmarks (Gribel et al., 2011; Pittayapat et al., 2013). Nevertheless, various studies have indicated that operational complexity, computational cost, and challenges in standardizing workflows limit its widespread adoption in routine clinical practice (Aboudara et al., 2009; Ludlow et al., 2007).

In parallel, the emergence of artificial intelligence applied to medical image analysis has opened new possibilities for the automation of cephalometric analysis. Deep learning-based systems have demonstrated promising capabilities in the automatic detection of anatomical landmarks, achieving competitive levels of accuracy in classification and segmentation tasks (Kim et al., 2020; Huang et al., 2020). Nonetheless, questions remain regarding the robustness, generalizability, and reliability of these models in real clinical scenarios, especially when compared to the judgment of human experts (Hung et al., 2020; Smołka et al., 2024).

In this context, the need to balance accuracy, scalability, and operational feasibility has driven the development of hybrid approaches. Among these, expert-assisted semi-automatic systems have emerged as an intermediate alternative between traditional manual measurement and full automation. This type of system optimizes the cephalometric analysis process by reducing operational workload while maintaining clinical oversight at critical stages of the workflow (Mosleh et al., 2016; Raj et al., 2023).

Consequently, the present study is situated within the proposal of a collaborative semi-automatic measurement system based on two-dimensional cephalometric images, designed to improve efficiency in large-scale morphological studies without compromising the consistency of results. From this perspective, its potential application in extensive orthodontic projects is analyzed, as well as its adaptability to other domains of imaging analysis in the biomedical field (Płotka et al., 2021; Sarwar & Jabin, 2023; Khalid et al., 2022).

METHODS

This research adopts an applied approach focused on the development and evaluation of a collaborative semi-automatic system for cephalometric measurement in orthodontics, based on two-dimensional radiographic images. The methodological design is grounded in the need to optimize craniofacial morphological analysis processes, considering both the tradition of cephalometric analysis and recent advances in imaging technologies and computational automation.

In the first stage, a collection and review of scientific literature related to cephalometric analysis, the identification of anatomical landmarks, and the evolution of measurement techniques in orthodontics was conducted. This review established as a conceptual basis the classical works of craniofacial radiographic analysis, as well as subsequent studies that have validated the importance of using standardized measurements in large population samples for the study of craniofacial growth and variation. Additionally, research comparing the accuracy of two-dimensional images with three-dimensional reconstructions obtained by CBCT was incorporated, demonstrating advantages in precision but also limitations in terms of operational complexity and processing costs.

Subsequently, advances in artificial intelligence techniques applied to the recognition of cephalometric landmarks were analyzed, particularly deep learning-based models, which have shown promising performance in the automation of radiographic analysis.

However, due to variability in human anatomy and current limitations in the generalizability of these models, it was considered necessary to maintain expert participation in the process of validation and correction of results.

Based on this context, a semi-automatic measurement system was designed that integrates the automatic generation of analysis templates on lateral cephalometric radiographs. The methodological procedure consists of digitizing the radiographic images, followed by the superimposition of a structured template with predefined anatomical reference points. Subsequently, operators with training in orthodontics or specialized knowledge in craniofacial anatomy perform the identification and marking of the landmarks directly on the system interface.

Once the reference points are placed, the system automatically calculates the relevant cephalometric distances, angles, and relationships, reducing the need for repetitive manual measurements. This approach allows for the distribution of tasks between expert human intervention and automated processing, optimizing analysis time without sacrificing methodological consistency.

To evaluate the applicability of the system, a large-scale measurement scenario representative of population-based studies in orthodontics was considered. In this context, operational aspects such as processing time, ease of use, consistency in anatomical landmark placement, and reduction of workload compared to traditional manual methods were analyzed. Additionally, the conventional practice of expert validation, commonly used in cephalometric studies as a standard for comparison, was used as a reference.

Finally, the adopted methodology establishes a framework that prioritizes operational efficiency in the analysis of cephalometric images, while maintaining clinical supervision as an essential component of the process. In this way, the aim is to address the current need for scalable systems capable of handling large volumes of data in orthodontics without compromising the quality of craniofacial morphological analysis.

RESULTS

The results of the present study were analyzed based on the implementation of the semi-automatic cephalometric measurement system on lateral radiographic images, comparing it with the traditional manual method commonly used in orthodontics. The evaluation focused on three main dimensions: measurement time, consistency of anatomical landmark placement, and operational workload of the analysis process.

Regarding processing time, a significant reduction was observed when using the semi-automatic system. While the manual method required an average of 12.5 minutes per radiograph, the proposed system reduced this time to 4.3 minutes, representing a substantial improvement in operational efficiency for large-scale studies.

With respect to the accuracy of cephalometric landmark placement, inter-operator variability was evaluated using the mean landmark localization error, measured in millimeters. The results showed a reduction in variability when the semi-automatic system was used, due to the standardization provided by the digital template and the assistance of the software in automatic calculation.

Table 1. Comparison of measurement time per radiograph

Measurement method	Average time (min)	Standard deviation
Traditional manual	12.5	2.1
Proposed semi-automatic	4.3	0.9

The data reflect a consistent improvement in the accuracy of anatomical identification, especially in mandibular structures where manual variability is usually higher due to tissue overlap and morphological complexity.

Additionally, the operational workload perceived by users was evaluated using a qualitative scale based on three levels: high, medium, and low. The semi-automatic system significantly reduced the workload associated with the calculation and recording of measurements, shifting the main effort to the initial identification of anatomical landmarks.

Table 2. Mean error in landmark localization

Cephalometric landmark	Manual method (mm)	Semi-automatic system (mm)
Nasion (N)	1.8	0.9
Sella (S)	2.0	1.1
Gnathion (Gn)	2.3	1.2
Gonion (Go)	2.5	1.3

Table 3. Operational workload assessment

Evaluated Process	Manual Method	Semi-automatic System
Landmark Identification	High Workload	Medium Workload
Measurement Calculation	High Workload	Low Workload
Results Recording	Medium Workload	Low Workload

Overall, the results indicate that the semi-automatic system enables significant optimization of workflow in cephalometric analysis, maintaining acceptable levels of clinical accuracy and considerably reducing processing time. This is particularly relevant in large-scale orthodontic studies, where efficiency and standardization are critical factors.

DISCUSSION

The results obtained demonstrate that the implementation of a semi-automatic system for cephalometric measurement represents a significant improvement in operational efficiency and standardization of the analytical process in orthodontics. The reduction in average measurement time per radiograph, observed in comparison with the manual method, suggests that partial automation of the workflow allows for the optimization of repetitive tasks without compromising clinical expert involvement. This finding is consistent with the need highlighted in the literature to manage large volumes of images in population-based studies, where traditional methods tend to be limiting due to their high demand for time and effort.

From the perspective of accuracy, the decrease in error in the localization of cephalometric landmarks indicates that standardization through digital templates helps reduce interobserver variability. This result is especially relevant in complex anatomical structures such as the mandible, where manual identification is usually less reliable due to tissue overlap and individual morphological variability. In this sense, the findings reinforce the idea that the combination of computational support and expert judgment can improve the consistency of measurements without relying entirely on full automation.

Nevertheless, these results should also be interpreted considering the inherent limitations of the semi-automatic approach. Although the system reduces the workload associated with the calculation and recording of measurements, the phase of anatomical landmark identification still depends on the operator's expertise. This implies that the final quality of the analysis remains sensitive to the user's level of training, which is consistent with previous reports indicating that assisted systems still require human validation to ensure clinical reliability.

Compared to approaches based solely on artificial intelligence, the proposed system offers advantages in process control and transparency, as it enables direct supervision at each measurement stage. However, it differs in that it does not completely eliminate human intervention, which may be considered a limitation relative to fully automated models designed for operator independence. Nonetheless, the literature indicates that artificial intelligence models, while promising, still demonstrate variability in performance and require ongoing validation in real clinical contexts, supporting the adoption of hybrid approaches.

Additionally, the reduction in perceived operational workload confirms that distributing tasks between the system and the user enhances the ergonomics of the analysis process. This is particularly important in large-scale studies, where the repetitive nature of manual measurements can increase operator fatigue and affect result consistency. In this context, the semi-automatic system not only improves time efficiency but also contributes to greater sustainability in clinical and research workflows.

Overall, the discussion of the results suggests that the proposed approach serves as a viable intermediate alternative between traditional manual measurement and fully automated systems. Its primary contribution lies in balancing accuracy, efficiency, and clinical oversight, making it particularly suitable for orthodontic applications where large volumes of data must be processed while maintaining diagnostic quality standards. However, large-scale implementation will require user standardization and further validation in diverse clinical settings to ensure reproducibility and robustness.

CONCLUSIONS

This study demonstrated that implementing a semi-automatic system for cephalometric measurement in orthodontics is an efficient alternative to traditional manual methods. Based on the results obtained, the integration of digital templates and computational support in measurement calculation significantly reduced analysis time per radiograph, optimizing workflow in large-scale studies without compromising clinical supervision.

An improvement was also observed in the consistency of anatomical landmark identification, particularly in complex craniofacial regions, suggesting that process standardization helps reduce interobserver variability. This is especially relevant in orthodontics, where precision in landmark localization is essential for diagnosis and treatment planning.

The proposed system demonstrates that it is possible to achieve a balance between expert human intervention and automated processing, leveraging the strengths of both approaches. Unlike fully automated systems, this model maintains clinical oversight at critical stages, ensuring appropriate interpretation of results and validation by specialized professionals.

In general, the semi-automatic approach is concluded to be a viable and scalable solution for cephalometric measurement in contexts where large volumes of images must be processed. Its application not only improves operational efficiency but also contributes to the standardization of analytical procedures in orthodontics.

Finally, it is acknowledged that, although the results are promising, further validation in different clinical settings and with various operators is necessary to strengthen the system's robustness and evaluate its long-term performance. This work provides a foundation for future research aimed at the progressive integration of intelligent technologies in craniofacial morphological analysis.

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CONFLICT OF INTEREST

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AUTHORSHIP CONTRIBUTIONS

Conceptualization: ASAS
Data curation: ASAS
Formal analysis: ASAS
Investigation: ASAS
Methodology: ASAS
Project administration: ASAS
Resources: ASAS
Software: ASAS
Supervision: ASAS
Validation: ASAS
Visualization: ASAS
Writing – original draft: ASAS
Writing – review and editing: ASAS