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Conventional vs. digital wax-up: a crossover study on accuracy and undergraduate student satisfaction

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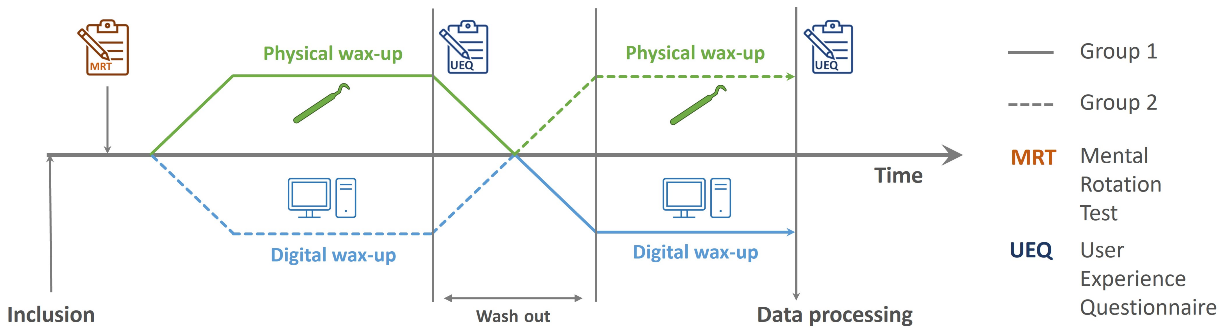


Physical wax-up
Physical wax-up
MRT
UEQ
UEQ
Time
Digital wax-up
Digital wax-up
Inclusion
Wash out
Data processing
Group 1
Group 2
MRT
Mental Rotation Test
UEQ
User Experience Questionnaire

Conventional vs. digital wax-up: a crossover study on accuracy and undergraduate student satisfaction

Abstract

Objectives

The aim of this study was to compare the accuracy and user experience of diagnostic wax-ups performed by dental students using conventional and digital Computer-Aided Design (CAD) methods.

Methods

A crossover design was implemented with 105 fourth-year dental students. Each participant completed diagnostic wax-ups using both methods on standardized 3D-printed models, with a one-week washout period. Spatial visualization skills were assessed via the Mental Rotation Test (MRT) prior to the wax-up tasks. The conventional method involved manual wax sculpting, while the digital method utilized Meshmixer 3.5 software for teeth adaptation. Accuracy was evaluated using Iterative Closest Point (ICP) algorithms and metrics such as mean squared distance, Chamfer distance, and Hausdorff distance. After each session, a user experience questionnaire was administered.

Results

The conventional method yielded significantly higher accuracy ($p < 0.001$) compared to the digital method. Nevertheless, students strongly preferred the digital approach for its ease of use ($p < 0.001$). MRT results showed no significant correlation between the 3D spatial skills and wax-up accuracy for both methods.

Conclusions

Conventional wax-ups demonstrated higher accuracy, while the digital method was favored for its user-friendliness. The absence of a correlation between spatial skills and performance suggests that other factors may influence outcomes. Digital solutions such as Meshmixer provide a cost-effective CAD alternative in resource-limited educational settings.

Clinical Significance

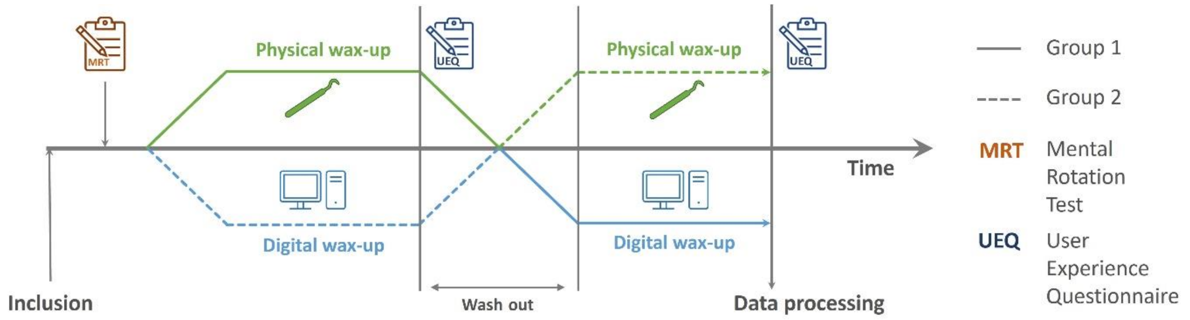
Using easily implementable CAD software in dental schools could allow more CAD training within the curriculum, helping bridge the gap between undergraduate training and postgraduate practice, where CAD is extensively used.

Keywords: Competency-Based Education; Computer-Aided Design; Education, Dental; Imaging, Three-Dimensional; Motor Skills.

Key findings:

- Conventional wax-ups were more precise, highlighting their higher accuracy.
- Students prefer digital wax-ups despite lower accuracy, due to their ease of use.
- No significant correlation between 3D visualization skills and wax-up accuracy.
- Meshmixer offers a CAD alternative for resource-limited dental education.

Graphical abstract:



I. Introduction

The success of prosthetic planning relies heavily on the accuracy of diagnostic wax-ups, which play a pivotal role in predicting the aesthetic and functional outcomes of dental restorations. These wax-ups are indispensable tools for evaluating the feasibility of complex treatments and ensuring the overall success of prosthetic rehabilitation [1–5]. Traditionally, diagnostic wax-ups have been created manually by sculpting wax on plaster models, a method that, despite its effectiveness, is labor-intensive and skill-dependent [5].

However, advances in digital technologies have revolutionized the field of dentistry. Computer-aided design (CAD) tools, combined with optical scanners and computer-controlled milling, now offer an alternative to manual techniques. These technologies aim to enhance efficiency and reproducibility within digital workflows [6–11]. Yet, adopting CAD methods for diagnostic wax-ups presents several challenges. These include high initial costs, continuous maintenance demands, and a steep learning curve for mastering new software [12,13].

While CAD technologies hold immense potential, comparative studies have revealed discrepancies in the accuracy and reliability of digital versus conventional methods. For instance, Abduo et al. [14] demonstrated that conventional wax-ups outperformed digital methods in certain dimensional criteria. Similarly, Mino et al. [15] highlighted that while digital tools provide volumetric data quickly, they often fail to match the nuanced precision achievable with manual techniques. Moreover, qualitative evaluations frequently emphasize the limitations of digital wax-ups in reproducing anatomical details such as contact points, cusp morphology, and axial contours [15,16].

In dental education, the integration of CAD tools poses unique pedagogical challenges. On one hand, conventional physical wax-ups remain central to teaching foundational manual dexterity and spatial visualization skills. On the other hand, the growing prevalence of CAD/CAM workflows in clinical and laboratory settings demands that students acquire proficiency in digital methods [12,17]. However, the financial burden of equipping dental schools with high-performance computers and specialized software can limit students' exposure to these tools, exacerbating inequities among students with varying levels of access to technology [13].

To address these challenges, there is a growing interest in leveraging open-source or low-cost digital tools that require minimal computing resources to bridge the gap between the professional demand for CAD expertise and the limited resources of many dental schools [13,15]. These tools offer an accessible entry point for students to develop basic CAD skills without the financial and logistical barriers associated with commercial software. By integrating these solutions into educational curricula, faculties can ensure broader access to CAD training while preparing students for future professional practices.

Wax-up performance evaluation, whether digital or conventional, introduces additional complexity. Current assessment methods rely heavily on subjective criteria, such as aesthetic scoring or student self-assessment, sometimes supplemented by software including E4D Compare (D4D Technologies (Richardson, TX, USA) for quantitative analysis [18,19]. While these tools offer valuable insights, they are not without limitations. For instance, the alignment of digital models, which is assumed to be perfect, inevitably introduces minor inaccuracies. Furthermore, most evaluations do not fully address the educational challenges involved, such as cognitive and manual learning processes, required to master CAD tools [15,20].

Another unexplored dimension is the role of spatial mental rotation abilities—the capacity to visualize and manipulate 3D objects mentally—in influencing wax-up performance [21]. This cognitive skill, while critical in conventional methods, may also play a role in digital workflows, where students interact with virtual models. Understanding this relationship could inform the design of more effective training programs that bridge the gap between physical and digital techniques.

This study aims to compare the accuracy and user experience of diagnostic wax-ups created using conventional and digital methods. The primary aim is to evaluate the dimensional accuracy of wax-ups through quantitative metrics. The secondary aims include assessing user satisfaction through structured questionnaires and exploring the role of cognitive factors, such as spatial mental rotation abilities, in wax-up performance. By integrating these perspectives, this study seeks to provide a comprehensive understanding of the strengths and limitations of both techniques, offering insights to optimize pedagogical strategies and better prepare the next generation of dental professionals for clinical practice.

The null hypotheses are that there is no difference in accuracy between diagnostic wax-ups created using conventional and digital methods, and that the order of practical sessions (whether digital followed by physical or physical followed by digital) in the crossover design does not influence the results

II. Method

II.1. Study Design and Participants

This crossover study design was implemented with 105 fourth-year dental students from the Dentistry Department of the Faculty of Health of [city anonymized], during the 2023–2024 academic year. Participants completed wax-ups using both conventional and digital methods during two separate 2.5-hour practical sessions, spaced one week apart to minimize washout effects and reduce “carry-over” effects (**Error! Reference source not found.**) [22].

Ethical approval was obtained from the Research Ethics Committee of the Federal University of [city anonymized] (Approval Number: 00011835-2023-1130-754). Informed consent was obtained by all the participants before their participation.

An a priori sample size calculation was performed using G*Power 3.1.9.7. The sample size calculation revealed that 94 participants were needed to achieve a power of 80% with an assumed effect size of 0.3 and an alpha of 0.05. Accordingly, 105 students were initially enrolled, and 95 students completed both practical sessions. The crossover design allowed direct intra-subject comparisons, reducing the impact of individual variability and improving the reliability of the findings.

II.2. Model Standardization

ANA-4 models (Frasaco GmbH, Tettnang, Germany), commonly used in preclinical fixed prosthetics training, were employed. Defects were introduced on four maxillary incisors to simulate realistic clinical conditions. The ANA-4 models, both with and without simulated defects, were scanned using a 3Shape E Series tabletop scanner (accuracy: 10 microns) (3Shape, Copenhagen, Denmark) to generate digital 3D representations. The scanned models were saved in Standard Tessellation Language (STL) format, which is commonly used in 3D printing and computer-aided design to represent surface geometry as a collection of triangular facets (**Error! Reference source not found.**). These STL files were processed using slicing software Chitubox Basic 1.9.4, (Shenzhen CBD Technology Co, Shenzhen, China)

To ensure accuracy in the 3D printing process, a calibration phase was performed first. A 20 mm-sided calibration cube was printed, and its dimensions were measured along all axes using a precision caliper. The measured dimensions were compared to the target values. The calibrated Photon Mono printer (Anycubic, Shenzhen, China), employing UV LCD technology (50 mm/h printing speed, 0.05 mm XY resolution, and 0.01 mm Z resolution), was then used to produce the 3D-printed models. A grey-colored water washable photopolymer resin (Elegoo, Shenzhen, China) was employed, and all models were printed in a vertical orientation. Standardized defective models were provided to all participants, while intact models served as aesthetic references.

II.3. Practical Procedures:

Students were trained on both methods through a one-hour theoretical session held two weeks before the practical sessions. The session included instructional videos on conventional and digital wax-up techniques, which were made available for further reference.

- **Conventional Method:** Students utilized Geo Natural Wax (Renfert, Hilzingen, Germany) to sculpt tooth morphology on their 3D-printed defective models, employing a variety of heated instruments such as carvers and wax knives. The session lasted 2.5 hours, followed by a user experience questionnaire.
- **Digital Method:** The digital wax-up process involved fitting an average tooth form from Christian Brenes' library of teeth and pontics onto virtual pretreatment models using Meshmixer 3.5 software (Autodesk, San Francisco, U.S.)[23]. Students refined the fitted forms by utilizing the Sculpt and Edit tools within the software to achieve the desired tooth morphology. This software was chosen for its accessibility, intuitive interface, and free license, making it particularly suitable for educational purposes. The session matched the conventional wax-up session in duration and was followed by the same user experience questionnaire to ensure consistent evaluation. The computers used for the digital wax-up were equipped with Intel Pentium Gold G5400 CPUs @ 3.70 GHz, 4 GB of DDR4 RAM with a frequency of 2666 MHz, and Intel UHD Graphics 610. These specifications, though modest, were sufficient to run the software efficiently in an educational setting.

II.4. Evaluation Metrics

Completed wax-ups were scanned using a 3Shape E Series tabletop scanner and converted into point clouds. These were aligned with the intact reference model using the Iterative Closest Point (ICP) algorithm, minimizing discrepancies [24–26]. To ensure robust accuracy measurements and mitigate the influence of wax residues and margin inconsistencies, we selected a global area of interest (AOI) covering the entire model surface. The alignment relied primarily on approximately 87% of the surface corresponding to unchanged anatomical regions, providing a stable reference and minimizing distortion from localized wax application or margin irregularities. Then, accuracy measurements (distance calculations) were conducted on the complete surface, including both unchanged and modified areas, to comprehensively assess the overall deformation pattern without bias. Three metrics were used to assess accuracy:

- **Mean Squared Distance (MSD):** This metric calculates the average squared distance between corresponding points on the wax-up and the reference model. By squaring the deviations, larger discrepancies are given more weight, making this metric particularly sensitive to significant misalignments across the entire surface.
- **Chamfer Distance:** Chamfer distance evaluates the proximity of each point on the wax-up model to the closest point on the reference model and vice versa. It captures both global and localized deviations by accounting for asymmetry in the alignment, ensuring a balanced representation of discrepancies between the two surfaces [27].
- **Hausdorff Distance:** Hausdorff distance identifies the single largest discrepancy between the farthest points on the wax-up and the reference model. This metric is particularly useful for detecting extreme outliers that may not significantly influence the overall average but could indicate problematic areas of the wax-up [28].

To ensure reliability, each metric was calculated five times, and the composite metric was computed using the averaged values.

II.5. Mental Rotation Test (MRT)

Before the practical sessions, participants completed a Mental Rotation Test (MRT), a standardized assessment of 3D spatial visualization skills. The test, elaborated by Vandenberg and Kuse from the original figures of Shepard and Metzler, measures the ability to mentally rotate 3D objects to determine congruence between different perspectives [29,30].

II.6. User Experience Evaluation

The User Experience Questionnaire - Short Version (UEQ-S) is a concise tool designed for the rapid evaluation of user experience in products, services, or processes [31]. It captures subjective perceptions of the user experience, focusing on key aspects such as efficiency, clarity, attractiveness, and stimulation. This shortened version of the questionnaire consists of 8 items (Supplementary 1) and is specifically designed to provide quick assessments while maintaining sufficient reliability for comparative studies. Each item is presented as a pair of opposing adjectives, allowing users to rate their experience on a 7-point scale. The UEQ-S evaluates both pragmatic qualities, such as ease of use and intuitive understanding, and hedonic qualities, including perceived enjoyment and originality during the experience. Its structure enables a rapid yet reliable analysis of user satisfaction.

II.7. Pseudonymization of Data:

Digital data collected during the practical sessions, including questionnaire responses and volumetric concordance rates, were pseudonymized by assigning a sequential identification number. This process was carried out in accordance with the recommendations of the General Data Protection Regulation for Education (GDPR-E) to minimize risks associated with the handling of personal data.

II.8. Statistical analysis

To achieve a robust statistical analysis, a composite metric was generated by combining the three individual measures: Mean Squared Distance, Chamfer Distance, and Hausdorff Distance. Each measure was normalized to a common scale to eliminate differences in their ranges, ensuring that the comparisons between them were reasonable. Normalization also accounted for variations in the scale and sensitivity of each metric. After normalization, the arithmetic mean of the three normalized values was calculated to produce the composite metric. This approach mitigates the limitations inherent to any single measure by integrating global discrepancies, localized deviations, and extreme outliers into a single, comprehensive deformation score. This metric provides a more reliable and holistic evaluation of the performance by balancing average deviations and extreme errors between the produced model and the target. Data normality was assessed using the Shapiro-Wilk test. If the data was not normally distributed, then appropriate nonparametric tests were applied. The Student's t-test was applied to normally distributed data, while the Wilcoxon signed-rank test was used for non-normally distributed data. Accordingly, the means of the two methods (i.e., conventional and digital) were compared using the Wilcoxon signed-rank test to determine differences. The strength and the direction of association between the MTR scores and the conventional and digital method were evaluated with Spearman's rank correlation. All the data was analyzed with Statistical Package for Social Sciences (SPSS Version 29, IBM). A P value of less than 0.05 was considered statistically significant.

III. Results

III.1. Primary objective: Comparative Accuracy

To address the primary objective, students who did not participate in both sessions were considered lost to follow-up. The analysis was only conducted on the 95 students who completed both practical sessions.

The calculations for the three-accuracy metrics were repeated five times, showing perfect convergence across iterations with identical results each time. This stability indicates robust measurements, confirming no errors occurred during the superimposition or distance calculations. The five iterations yielded identical results, confirming the absence of systematic error and ensuring precise evaluation between the wax-ups and the target.

Among the 95 participants, 66 (69.5%) of the participants achieved lower deformation scores using the conventional method. Lower deformation scores indicate closer alignment with the target model. For the conventional physical wax-up method, data distribution was centered around a mean (±SD) of 0.7± 0.2 and a range of: 0.6 and 0.8 indicating moderate dispersion (**Error! Reference source not found.**). Similarly, for the digital wax-up method, the data were centered around a mean of 0.8 ± 0.2 and a range of 0.7 to 0.9 (**Error! Reference source not found.**). Representative examples of these dimensional discrepancies are illustrated in **Error! Reference source not found.**, showing differences between wax-ups and the reference model using color maps.

The mean deformation index from both the digital and the conventional methods was compared. The results of the statistical analysis showed statistically significant differences between the methods. In particular, the conventional method had significantly lower deformation indices ($P<0.001$), demonstrating greater accuracy.

To evaluate potential sequence effects in this crossover design, a Mann-Whitney test was performed, testing the null hypothesis that the order of practical sessions did not influence results [32].
Statistical analysis showed no significant difference in the mean deformation index between the two arms of the crossover design ($P = 0.199$) (**Error! Reference source not found.**).

III.2. Mental rotation test and Satisfaction

Mental rotation test (MRT):

The MRT was conducted prior to the practical sessions, with responses scored according to the official grading scale. Randomly selected tests (n=20) were reassessed to ensure grading accuracy. The distribution of MRT scores had a mean of 18.08± 7.52 (maximum score= 40). Most scores ranged between 13 and 22.

Association:

The relationship between MRT scores (independent variable) and wax-up performance (dependent variables: results from the conventional and digital methods) was analyzed using Spearman's correlation. The analysis revealed no significant correlation between MRT scores and wax-up performance for either method. Specifically, the correlation with the conventional method was not significant ($P = 0.847$), and similarly, the correlation with the digital method was also not significant ($P = 0.140$).

III.3. User experience evaluation

The analysis of data collected from students, processed using the UEQ-S analysis tool, revealed that the experience provided by the digital method was perceived as significantly greater than the conventional method. Results showed statistically significant differences in favor of the digital approach in terms of overall experience ($p < 0.001$), pragmatic quality ($p = 0.001$), and hedonic quality ($p < 0.001$).

From a pragmatic perspective, students perceived the digital method as more intuitive and efficient. On a hedonic level, this approach was judged to be more stimulating and engaging. These findings highlight a clear preference for the digital format in practical sessions (**Error! Reference source not found.**).

IV. Discussion

The results of the current study demonstrate that fourth-year dental students from the Faculty of Dental Surgery in [city anonymized] achieved greater accuracy with conventional wax-ups compared to digital wax-ups, as measured by the primary outcome metric. Interestingly, despite the higher accuracy of the conventional method, students expressed a clear preference for the digital approach, as indicated by the user experience questionnaires. Furthermore, the Mental Rotation Test (MRT) scores showed no significant correlation with performance in either method, suggesting that strong three-dimensional visualization skills are not a prerequisite for success in these exercises.

The use of objective digital metrics as primary outcome measure reduced individual biases associated with subjective human assessments. By employing a composite deformation score integrating Mean Squared Distance, Chamfer Distance, and Hausdorff Distance, this study provides a comprehensive evaluation of the differences between the student-produced wax-ups and the target model. This approach mitigates the limitations inherent in any single metric, balancing average deviations and extreme errors to offer a holistic assessment of performance. While the findings of this study are supported by some previous studies, they are also contradicted by others. For instance, Abduo et al.

[14] found that conventional wax-ups outperformed digital methods in certain dimensional criteria, similar to the present results. Mino et al. [15] also highlighted that while digital tools offer quick volumetric data, they often fail to match the nuanced precision achievable with manual techniques. Contradictory to these findings, other studies have reported no significant differences between the methods or have emphasized the potential of digital tools to produce more comparable results with adequate training [33–35]. These divergences may be due to variations in evaluation criteria, the specific digital tools used, and the participants' familiarity with CAD software.

Comparing conventional and digital methods for wax-up creation raises questions about learning curves and the impact of regular practice on performance. While participants had solid theoretical knowledge and practical skills from prior courses, including prior experience sculpting wax teeth for dental anatomy, they had not previously completed wax-ups as part of a prosthetic project. This distinction may partly explain the observed differences in performance, as the demands of diagnostic wax-ups extend beyond basic anatomical replication to include functional and aesthetic considerations.

The initial unfamiliarity with digital design software presumably further contributed to the lower accuracy observed in digital wax-ups. This is consistent with previous findings where it was reported that dental students often exhibit limited knowledge of CAD/CAM systems, restoration design, and ceramic materials (mean ~2.3/5), highlighting the steep learning curve associated with mastering such tools [17]. Moreover, it was also reported that there was a positive correlation between the number of years in dental school and more favorable attitudes toward CAD/CAM technology, emphasizing the importance of sustained exposure to these tools throughout the curriculum. Future studies could explore how repeated use of digital tools narrows the accuracy gap, enhances skill acquisition, and improves student confidence in their ability to use CAD/CAM systems effectively.

A key achievement of this study was the successful implementation of Meshmixer on 25 low-specification computers provided by the faculty. This initiative addressed a critical challenge in dental education: the accessibility of CAD tools in resource-constrained environments. Specialized dental CAD software, such as 3Shape or Exocad, often require high-performance computers and significant financial investment for licenses and maintenance[12,13]. By contrast, Meshmixer is free, open-source, and has minimal hardware requirements, making it an attractive alternative for educational purposes [15].

This aligns with observations by Alhamed et al., who found that 80.3% of students identified the high cost of CAD/CAM equipment as a significant barrier, and with Blackwell et al. , who highlighted high initial investment costs, ongoing maintenance commitments, and concerns about rapid technological obsolescence as key reasons for the limited adoption of CAD/CAM technology, particularly in resource-limited settings [12,17]. The ability to utilize Meshmixer on existing faculty computers without costly upgrades ensured equal access to digital wax-up training while also allowing students to install the software on personal devices for extended practice. This flexibility presumably contributed to the high satisfaction scores for the digital method by removing technical barriers and encouraging self-directed learning.

In contrast, students often have only brief access to CAD tools during training, with limited opportunities for hands-on workshops, highlighting the need for more practical and accessible solutions to support skill development [17,19]. The COVID-19 pandemic underscored the importance of such measures, aligning with the American Dental Education Association's recommendations for innovative teaching methods to maintain practical training [13,36,37]. By leveraging affordable and accessible digital tools such as Meshmixer, this study demonstrates how equitable access to CAD/CAM training can be achieved while fostering student engagement and skill development.

Despite the lower accuracy of digital wax-ups, students rated the digital method significantly higher in terms of user experience. This preference may be attributed to several factors. A majority of students demonstrate familiarity with digital tools, which potentially enhanced their engagement when using software such as Meshmixer. The software's intuitive and interactive interface allowed for easier manipulation of 3D models, making the process more stimulating and less physically demanding than manual sculpting. Additionally, the incorporation of digital methods aligns with current technological trends in dentistry, reinforcing the relevance of their training and increasing student motivation.

These findings align with Alhamed et al., who reported that 87% of students view CAD/CAM as the future of dentistry. This highlights the importance of integrating digital tools into dental curricula to enhance student engagement and prepare them for the evolving landscape of clinical practice [17].

The lack of significant correlation between MRT scores and wax-up performance indicates that mental visualization skills, while often associated with manual dexterity, may not be critical for success in these exercises. Instead, success appears to rely more on procedural understanding, practice, and familiarity with the tools. The average MRT score observed in this study (18.08/40) is aligned with those reported in previous studies [38,39]. These comparable results suggest that the MRT performance observed in the present cohort is consistent with broader population norms, reinforcing the validity of the sample. However, it is worth pointing out that the MRT may not fully capture the specific spatial skills required for dental modeling. Exploring alternative assessments, such as Shepard and Metzler's Spatial Visualization Test or Cooper's Rotation Test, could provide deeper insights into the cognitive abilities most relevant to wax-up performance.

The successful use of low-specification computers and free software such as Meshmixer demonstrates a viable model for integrating digital wax-up training into dental education, even in institutions with limited resources. This approach can help bridge the gap between the need for CAD proficiency and the financial and logistical constraints often faced by educational programs. Faculties can enhance their readiness for clinical practice by providing students with early exposure to digital tools, where digital workflows are increasingly prevalent.

While Meshmixer served effectively as an introductory tool, it lacks some of the advanced functionalities and precision of dedicated dental CAD software. To fully prepare students for professional environments, curricula should consider a phased approach:

- Introductory training with accessible tools: Begin with open-source software i.e. Meshmixer to teach fundamental CAD concepts and skills.
- Progressive exposure to specialized software: Introduce students to professional dental CAD software as they advance, allowing them to apply foundational skills in more sophisticated platforms.
- Blended learning strategies: Combine conventional and digital methods to ensure students develop both manual dexterity and digital proficiency.

This strategy addresses both the current resource constraints and the necessity of equipping students with competencies relevant to modern dental practices.

The current study is subject to certain constraints that provide obvious opportunities for further exploration. While participants had prior experience with wax modeling for anatomy, they lacked experience with diagnostic wax-ups and digital design software, which may have influenced their performance and the observed differences between methods. Additionally, while Meshmixer was practical for educational purposes, it may not fully represent the capabilities of specialized dental CAD software. Furthermore, models were printed vertically; although practical, previous studies indicated that printing orientation significantly influences the accuracy and mechanical properties of printed models [40,41]. Another methodological concern is the definition of the area of interest (AOI). Using a global AOI covering the entire surface might dilute measurable differences specific to modified wax-up regions, potentially underestimating localized discrepancies and thereby favoring digital wax-ups due to their generally smoother transitions. Despite using a global AOI that could theoretically benefit digital wax-ups, our findings indicated significantly greater accuracy in conventional wax-ups, suggesting an intrinsic precision advantage that remains evident even under conditions favorable to digital techniques. Finally, the study was conducted at a single institution, potentially limiting the generalizability of the findings. Future studies involving multiple institutions, extended training periods, and comparisons with advanced CAD software could provide a more comprehensive understanding of the effectiveness of digital wax-up methods in dental education.

V. Conclusion

This study demonstrates that fourth-year dental students achieve greater accuracy with conventional wax-ups but show a strong preference for the digital method due to its intuitive and engaging nature. The successful deployment of Meshmixer on 25 low-specification faculty computers addressed critical barriers to CAD training, providing an accessible and scalable solution for resource-constrained institutions. The findings underscore the importance of adapting curricula to include both conventional and digital competencies, ensuring that students are prepared for the evolving demands of modern dentistry. Future research should explore the impact of extended training, the use of advanced CAD software, and the integration of innovative teaching strategies to further enhance skill development and educational outcomes.

VI. Bibliography:

[1] Braly BV. A preliminary wax up as a diagnostic aid in occlusal rehabilitation. J Prosthet Dent 1966;16:728–30. https://doi.org/10.1016/0022-3913(66)90151-X.

[2] Marques S, Ribeiro P, Gama C, Herrero-Climent M. Digital guided veneer preparation: A dental technique. J Prosthet Dent 2024;131:554–9. https://doi.org/10.1016/j.prosdent.2022.04.035.

[3] Preston JD. A systematic approach to the control of esthetic form. J Prosthet Dent 1976;35:393–402. https://doi.org/10.1016/0022-3913(76)90006-8.

[4] Saeidi Pour R, Engler MLPD, Edelhoff D, Prandtner O, Frei S, Liebermann A. A patient-calibrated individual wax-up as an essential tool for planning and creating a patient-oriented treatment concept for pathological tooth wear. Int J Esthet Dent 2018;13:476–92.

[5] Simon H, Magne P. Clinically Based Diagnostic Wax-up for Optimal Esthetics: The Diagnostic Mock-up. J Calif Dent Assoc 2008;36:355–62. https://doi.org/10.1080/19424396.2008.12221500.

[6] Beuer F, Schweiger J, Edelhoff D. Digital dentistry: an overview of recent developments for CAD/CAM generated restorations. Br Dent J 2008;204:505–11. https://doi.org/10.1038/sj.bdj.2008.350.

[7] Cervino G, Fiorillo L, Arzukanyan AV, Spagnuolo G, Cicciù M. Dental Restorative Digital Workflow: Digital Smile Design from Aesthetic to Function. Dent J 2019;7:30. https://doi.org/10.3390/dj7020030.

[8] Davidowitz G, Kotick PG. The use of CAD/CAM in dentistry. Dent Clin North Am 2011;55:559–70, ix. https://doi.org/10.1016/j.cden.2011.02.011.

[9] Marsango V, Bollero R, D'Ovidio N, Miranda M, Bollero P, Barlattani A. Digital work-flow. ORAL Implantol 2014;7:20–4.

[10] Suese K. Progress in digital dentistry: The practical use of intraoral scanners. Dent Mater J 2020;39:52–6. https://doi.org/10.4012/dmj.2019-224.

[11] Sulaiman TA. Materials in digital dentistry—A review. J Esthet Restor Dent 2020;32:171–81. https://doi.org/10.1111/jerd.12566.

[12] Blackwell E, Nesbit M, Petridis H. Survey on the use of CAD-CAM technology by UK and Irish dental technicians. Br Dent J 2017;222:689–93. https://doi.org/10.1038/sj.bdj.2017.407.

[13] Kim H-H, Lee J-H, Ha S-R, Choi Y-S. Implementation of CAD/CAM program in a nonface-to-face classroom environment due to the COVID-19 pandemic. J Dent Educ 2023;87:198–207. https://doi.org/10.1002/jdd.13112.

[14] Abduo J, Bennamoun M, Tennant M. Influence of Conventional and Digital Wax-ups on Axial Tooth Contour. Int J Periodontics Restor Dent 2015;35.

[15] Mino T, Kurosaki Y, Tokumoto K, Higuchi T, Nakanoda S, Numoto K, Tosa I, Kimura-Ono A, Maekawa K, Kim TH, Kuboki T. Rating criteria to evaluate student performance in digital wax-up training using multi-purpose software. J Adv Prosthodont 2022;14:203–11. https://doi.org/10.4047/jap.2022.14.4.203.

[16] Elgreatly A, Mahrous A, Clark WA, De Kok IJ, Qian F, Tsujimoto A. Students' perception of digital waxing software for dental anatomy education. J Oral Sci 2022;64:178–80. https://doi.org/10.2334/josnusd.22-0004.

[17] Alhamed FJ, Neiva GF, Bak S-Y, Karl E, Inglehart MR. Pre-doctoral dental students' computer-aided design/computer-aided manufacturing-related education, knowledge, attitudes and behavior: A national survey. J Dent Educ 2023;87:562–71. https://doi.org/10.1002/jdd.13144.

[18] Abdalla R, Bishop SS, Villasante-Tezanos AG, Bertoli E. Comparison between students' self-assessment, and visual and digital assessment techniques in dental anatomy wax-up grading. Eur J Dent Educ Off J Assoc Dent Educ Eur 2021;25:524–35. https://doi.org/10.1111/eje.12628.

[19] Chiang H, Staffen A, A Abdulmajeed A, Janus C, Bencharit S. Effectiveness of CAD/CAM technology: A self-assessment tool for preclinical waxing exercise. Eur J Dent Educ 2021;25:50–5. https://doi.org/10.1111/eje.12576.

[20] Siegel SC, Kramer SB, Deranek KM. Lean Methods Applied to CAD/CAM Pedagogy in the Dental Simulation Laboratory. J Dent Educ 2019;83:1081–91. https://doi.org/10.21815/JDE.019.100.

[21] Caissie AF, Vigneau F, Bors DA. What does the Mental Rotation Test Measure? An Analysis of Item Difficulty and Item Characteristics. Open Psychol J 2009;2:94–102. https://doi.org/10.2174/1874350100902010094.

[22] Mills EJ, Chan A-W, Wu P, Vail A, Guyatt GH, Altman DG. Design, analysis, and presentation of crossover trials. Trials 2009;10:27. https://doi.org/10.1186/1745-6215-10-27.

[23] Brenes C. 3D Teeth Library [dataset]. Meshmixer, Autodesk. 2013. Available from: [https://www.dropbox.com/scl/fi/ku38mxcc00h8hf7loincb/Brenes-Tooth-Pontic-Libraries.zip?rlkey=3ffm3w6gbdwmfgu5bgcl22j7s&st=cfh9vapl&dl=0].

[24] Delibasis K, Asvestas PA, Matsopoulos GK. Multimodal genetic algorithms-based algorithm for automatic point correspondence. Pattern Recognit 2010;43:4011–27. https://doi.org/10.1016/j.patcog.2010.06.009.

[25] Besl PJ, McKay ND. Method for registration of 3-D shapes. Sens. Fusion IV Control Paradig. Data Struct., vol. 1611, SPIE; 1992, p. 586–606. https://doi.org/10.1117/12.57955.

[26] Truchetto T, Dumoncel J, Nabet C, Galibourg A. Computer-assisted evaluation and feedback of a complete student class for preclinical tooth preparation. J Dent Educ 2023;87 Suppl 3:1776–9. https://doi.org/10.1002/jdd.13183.

[27] Elinas P. Matching Maximally Stable Extremal Regions Using Edge Information and the Chamfer Distance Function. 2010 Can. Conf. Comput. Robot Vis., 2010, p. 17–24. https://doi.org/10.1109/CRV.2010.10.

[28] Huttenlocher DP, Klanderman GA, Rucklidge WJ. Comparing images using the Hausdorff distance. IEEE Trans Pattern Anal Mach Intell 1993;15:850–63. https://doi.org/10.1109/34.232073.

[29] Shepard RN, Metzler J. Mental rotation of three-dimensional objects. Science 1971;171:701–3. https://doi.org/10.1126/science.171.3972.701.

[30] Vandenberg SG, Kuse AR. Mental rotations, a group test of three-dimensional spatial visualization. Percept Mot Skills 1978;47:599–604. https://doi.org/10.2466/pms.1978.47.2.599.

[31] Schrepp M, Hinderks A, Thomaschewski J. Design and Evaluation of a Short Version of the User Experience Questionnaire (UEQ-S). Int J Interact Multimed Artif Intell 2017;4:103. https://doi.org/10.9781/ijimai.2017.09.001.

[32] Lim C-Y, In J. Considerations for crossover design in clinical study. Korean J Anesthesiol 2021;74:293–9. https://doi.org/10.4097/kja.21165.

[33] Chisnoiu AM, Staicu AC, Kui A, Chisnoiu RM, Iacob S, Fluerașu M, Buduru S. Smile Design and Treatment Planning-Conventional versus Digital-A Pilot Study. J Pers Med 2023;13:1028. https://doi.org/10.3390/jpm13071028.

[34] Douglas RD, Hopp CD, Augustin MA. Dental students' preferences and performance in crown design: conventional wax-added versus CAD. J Dent Educ 2014;78:1663–72.

[35] Mocelin R de C, Penteado MM, Pierre FZ, Saraiva ACV, Uemura ES, da Silva JMF. Assessment of patient and dentist preference between conventional and digital diagnostic waxing. Int J Esthet Dent 2021;16:300–9.

[36] France K, Hangorsky U, Wu C-W, Sollecito TP, Stoopler ET. Participation in an existing massive open online course in dentistry during the COVID-19 pandemic. J Dent Educ 2021;85:78–81. https://doi.org/10.1002/jdd.12496.

[37] Galibourg A, Maret D, Monsarrat P, Nasr K. Impact of COVID-19 on dental education: How could pre-clinical training be done at home? J Dent Educ 2020;84:949. https://doi.org/10.1002/jdd.12360.

[38] Nazareth A, Herrera A, Pruden SM. Explaining sex differences in mental rotation: role of spatial activity experience. Cogn Process 2013;14:201–4. https://doi.org/10.1007/s10339-013-0542-8.

[39] Peters M. Sex differences and the factor of time in solving Vandenberg and Kuse mental rotation problems. Brain Cogn 2005;57:176–84. https://doi.org/10.1016/j.bandc.2004.08.052.

[40] Shim JS, Kim J-E, Jeong SH, Choi YJ, Ryu JJ. Printing accuracy, mechanical properties, surface characteristics, and microbial adhesion of 3D-printed resins with various printing orientations. J Prosthet Dent 2020;124:468–75. https://doi.org/10.1016/j.prosdent.2019.05.034.
[41] Williams A, Bencharit S, Yang I-H, Stilianoudakis SC, Carrico CK, Tüfekçi E. Effect of print angulation on the accuracy and precision of 3D-printed orthodontic retainers. Am J Orthod Dentofac Orthop Off Publ Am Assoc Orthod Its Const Soc Am Board Orthod 2022;161:133–9. https://doi.org/10.1016/j.ajodo.2021.01.020.

VII. Figures:

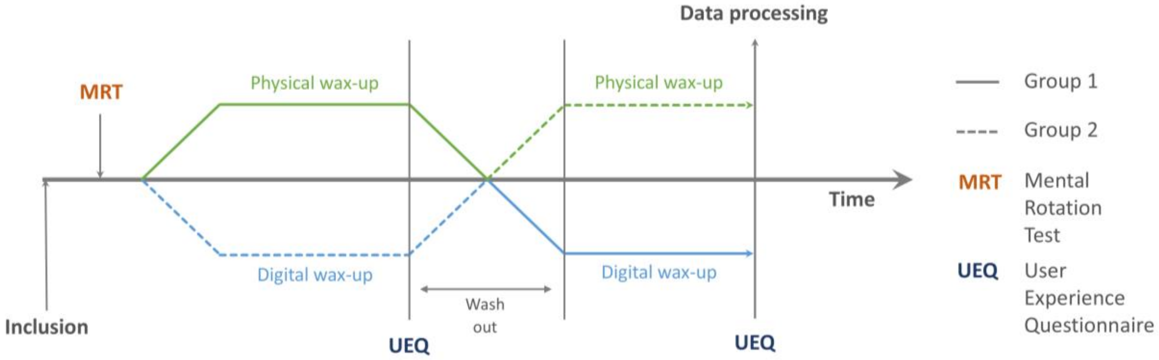


Fig.1: Crossover design for digital and physical practical training sessions

Fig.2 : Left: Digital model of the scanned dental arch with simulated defects. Right: Digital model of the scanned dental arch without defects.

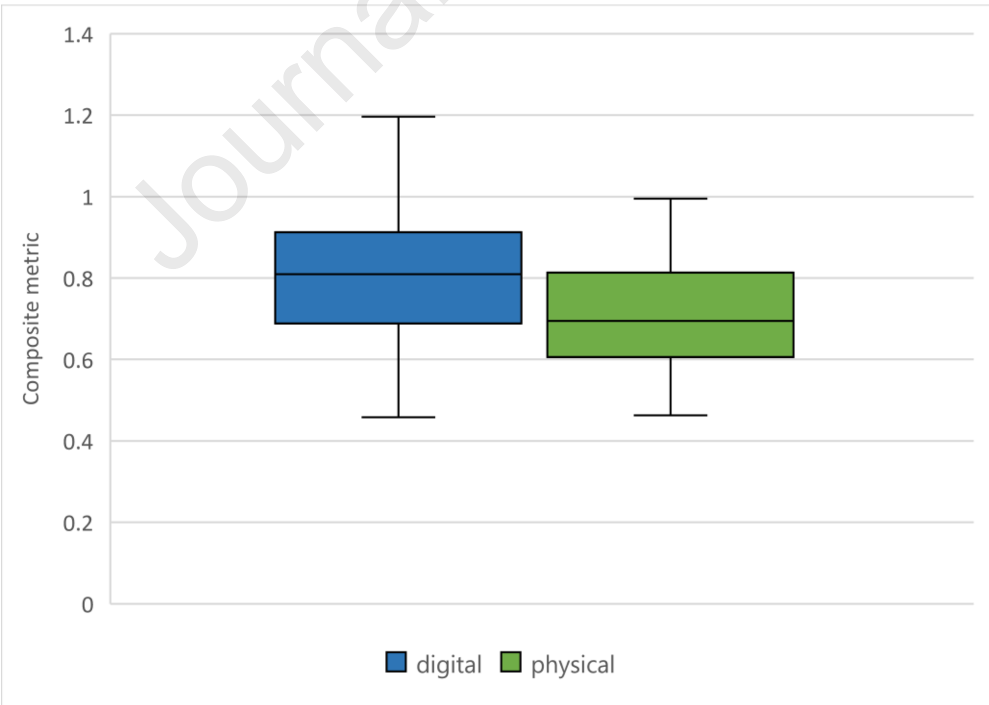


Fig.3: Boxplot comparing deformation indices for digital (blue) and conventional (green) wax-ups. The conventional method shows a lower median and less variability. The composite metric combines Mean Squared Distance, Chamfer Distance, and Hausdorff Distance, normalized and averaged to integrate global discrepancies, localized deviations, and outliers. A lower value indicates a closer match to the target (gold standard).

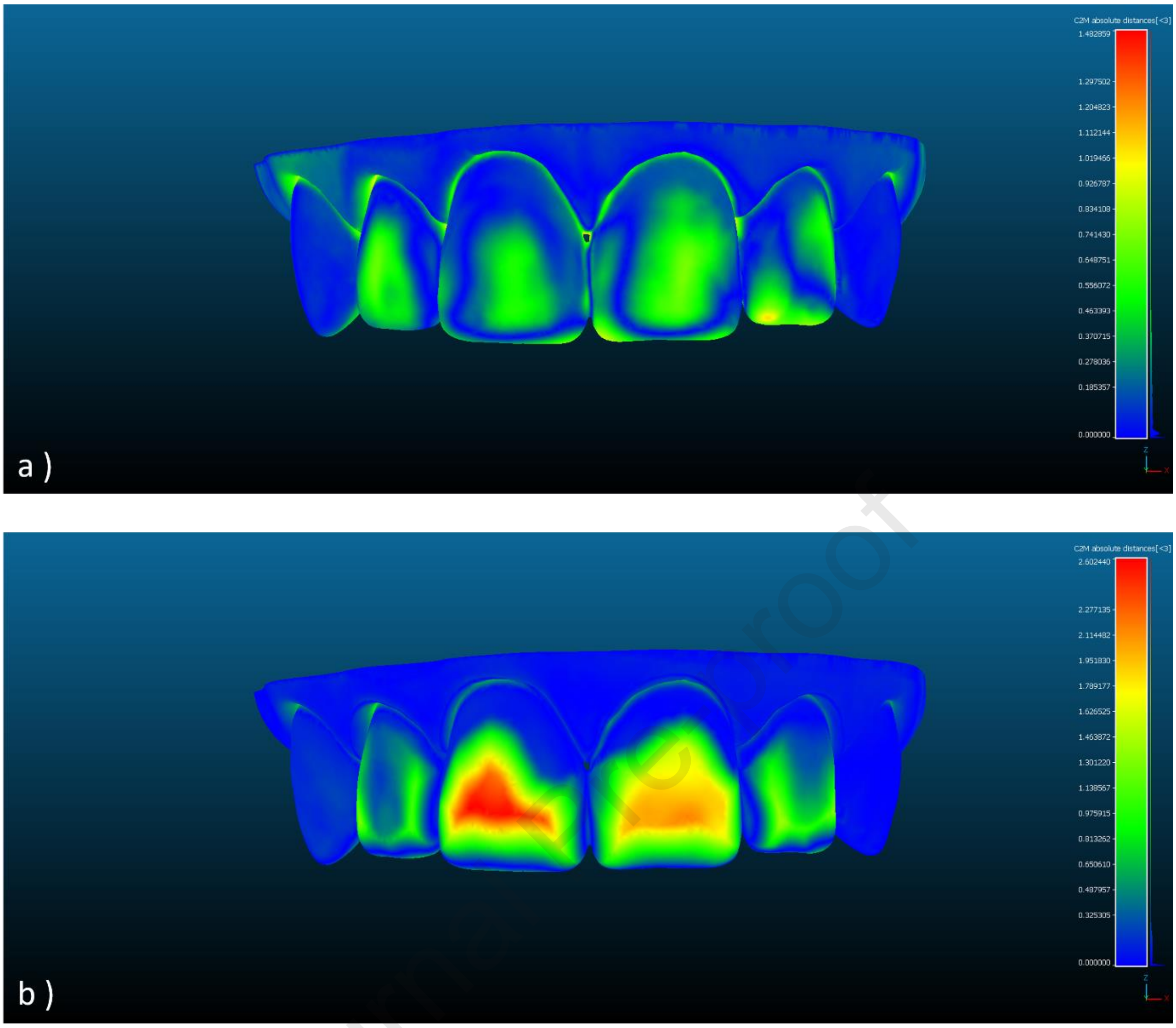


Fig.4: Visualization of dimensional discrepancies between wax-ups and the reference model, obtained with CloudCompare software (v2.13.2). The color maps illustrate distances (in mm), with a gradient ranging from blue (minimum deviation) through green and yellow to red (maximum deviation). (a) Conventional physical wax-up (maximum deviation: 1.4 mm). (b) Digital wax-up (maximum deviation: 2.6 mm), showing larger discrepancies compared to the physical method.

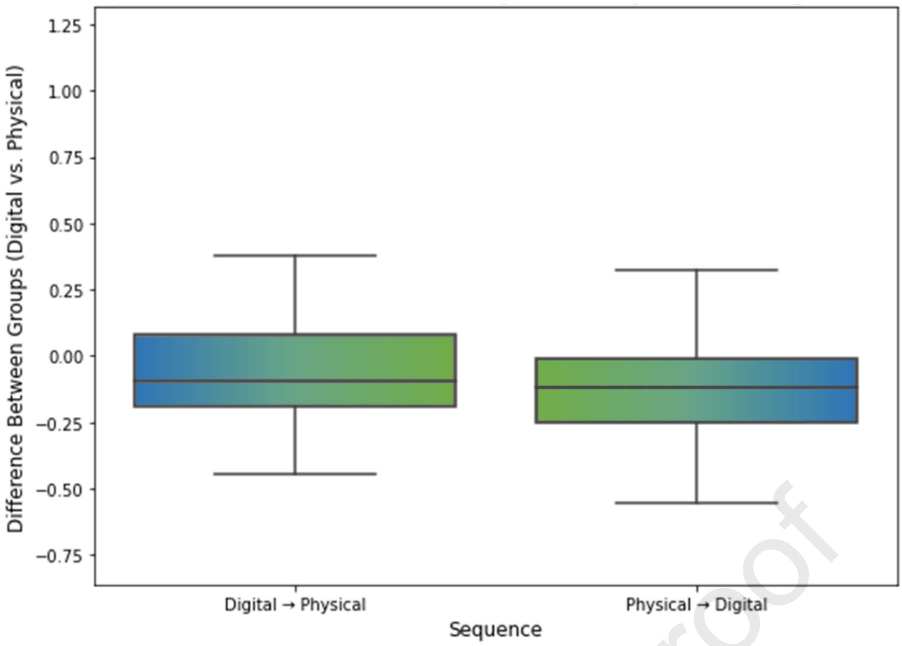


Fig.5: Effect of sequence on differences between digital and conventional wax-ups. The color gradient from blue to green corresponds to the group that performed digital followed by physical wax-ups, whereas the gradient from green to blue indicates the group that performed physical followed by digital wax-ups.

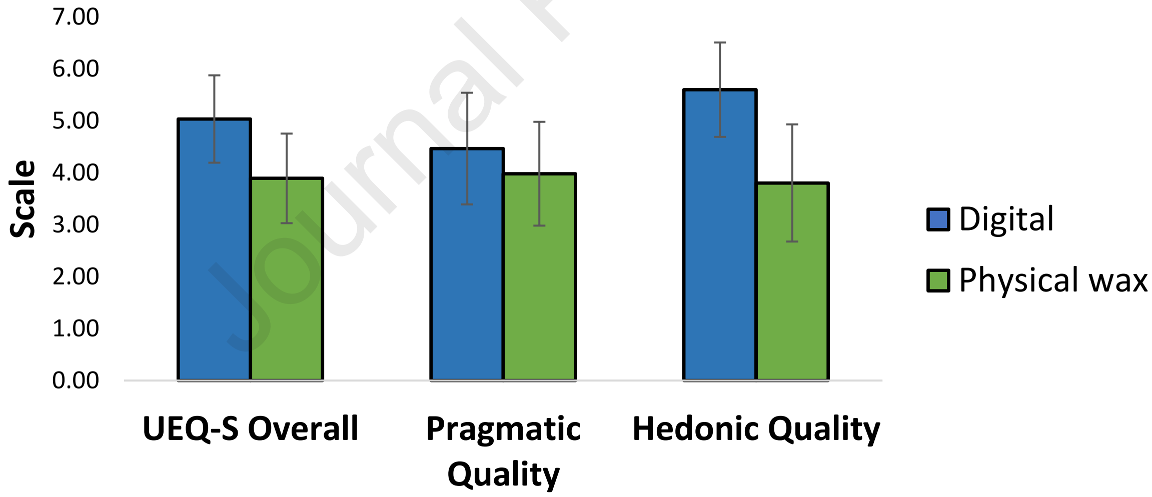
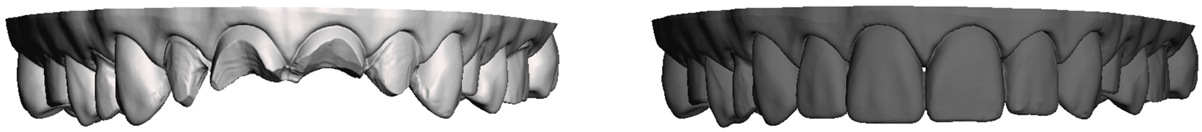
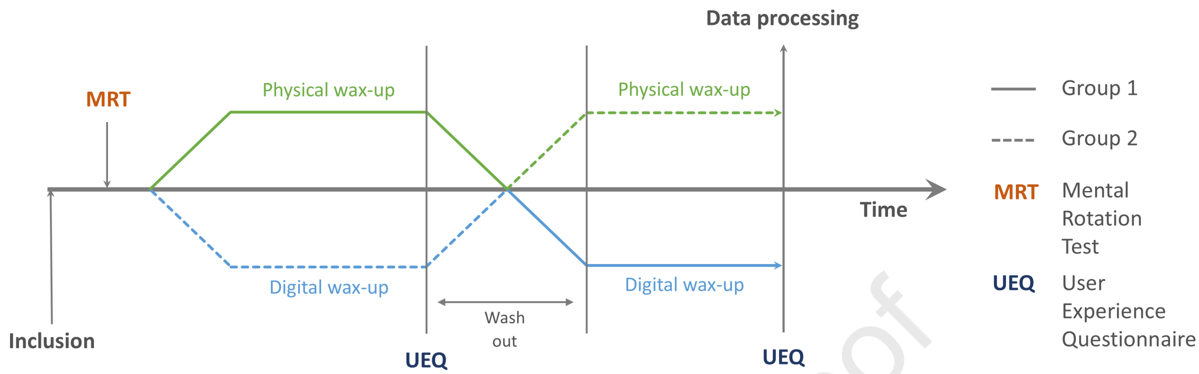
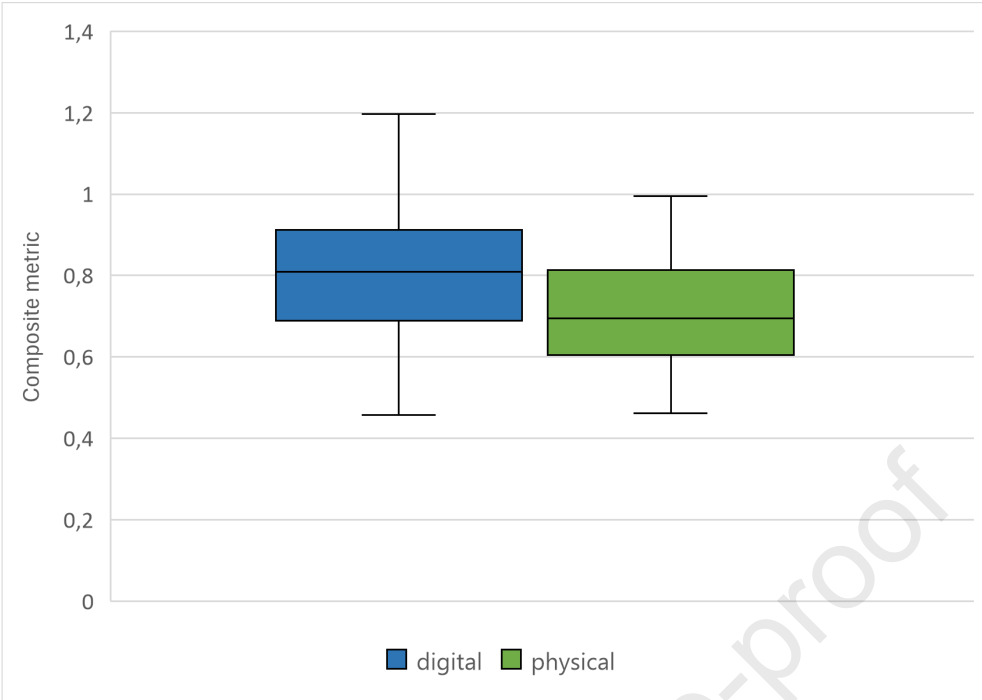
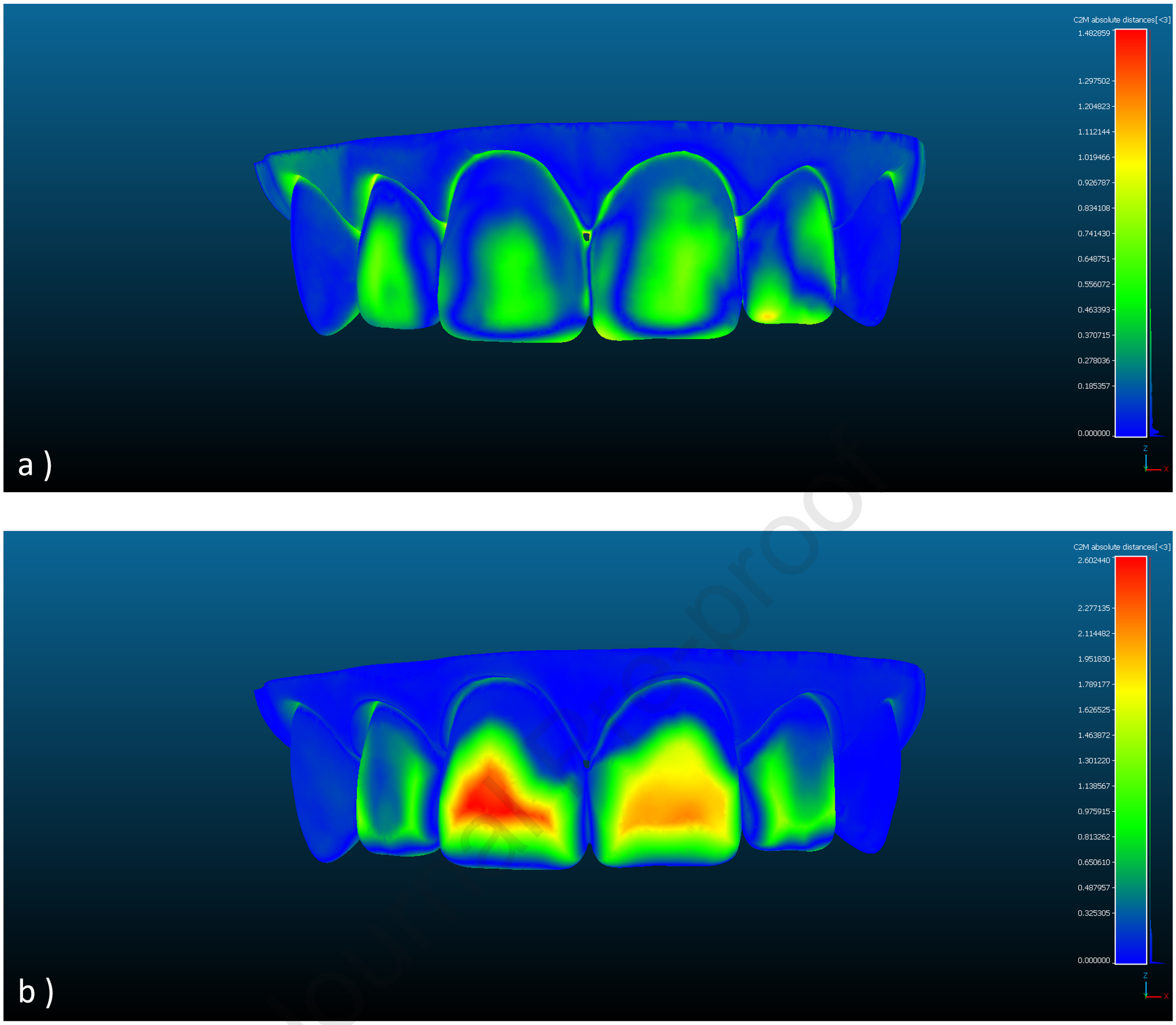


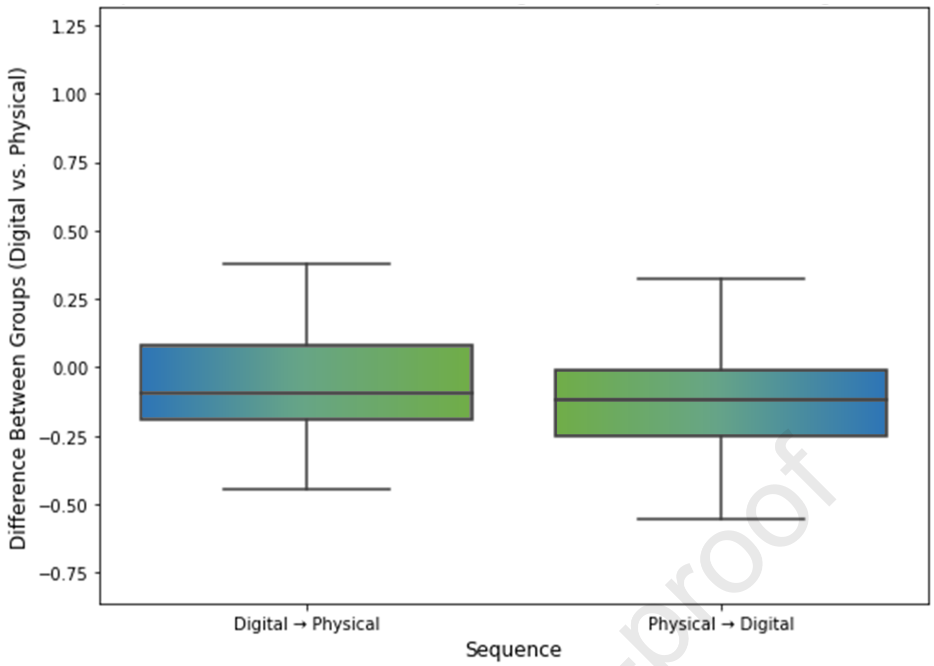
Fig.6: Bar chart comparing UEQ-S scores for digital (blue) and conventional (green) methods. Includes overall experience, pragmatic quality, and hedonic quality, with error bars representing confidence intervals

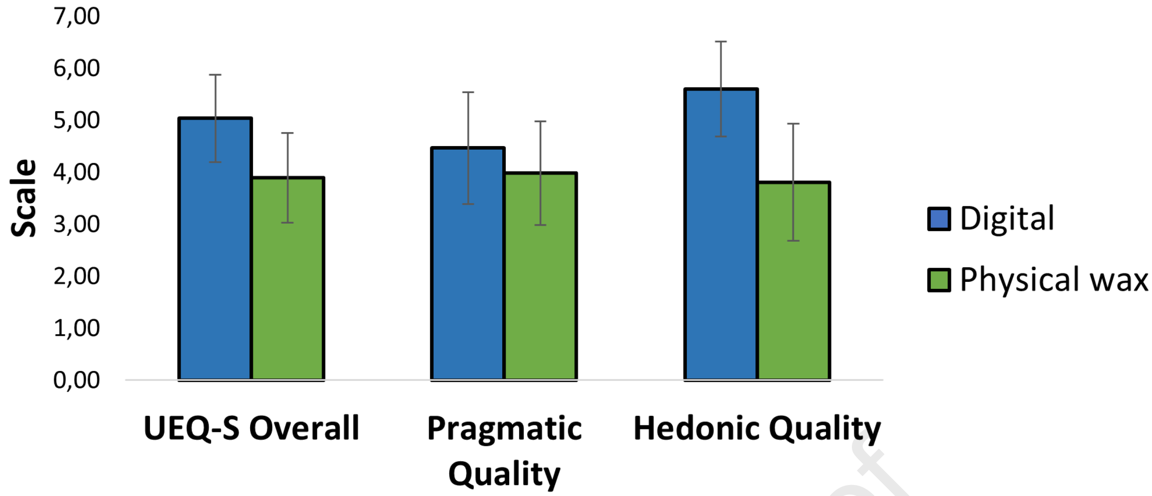



Data processing
MRT
Physical wax-up
Physical wax-up
Time
Digital wax-up
Digital wax-up
Wash
out
Inclusion
UEQ
UEQ
Group 1
Group 2
MRT Mental Rotation Test
UEQ User Experience Questionnaire


1,4
1,2
1
0,8
0,6
0,4
0,2
0
Composite metric
digital
physical


C2M absolute distances[<3]
1.482859
1.297502
1.204823
1.112144
1.019466
0.926787
0.834108
0.741430
0.648751
0.556072
0.463393
0.370715
0.278036
0.185357
0.000000
Z
X
a)
C2M absolute distances[<3]
2.602440
2.277135
2.114482
1.951830
1.789177
1.626525
1.463872
1.301220
1.138567
0.975915
0.813262
0.650610
0.487957
0.325305
0.000000
Z
X
b)


1.25
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
Difference Between Groups (Digital vs. Physical)
Digital → Physical
Physical → Digital
Sequence


7,00
6,00
5,00
4,00
3,00
2,00
1,00
0,00
Scale
UEQ-S Overall
Pragmatic Quality
Hedonic Quality
Digital
Physical wax

Key findings:

- Conventional wax-ups were more precise, highlighting their higher accuracy.
- Students prefer digital wax-ups despite lower accuracy, due to their ease of use.
- No significant correlation between 3D visualization skills and wax-up accuracy.
- Meshmixer offers a CAD alternative for resource-limited dental education.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: