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Galaxy Publication

Educational Impact of 3D-Printed Cleft Lip and Palate Phantom Models in Undergraduate Orthodontic Training

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ABSTRACT

This study explored how the use of 3D-printed phantom heads representing cleft lip and palate (CLP) affects learning and satisfaction in fourth-year dental students at J. W. Goethe University Frankfurt. The aim was to determine whether hands-on interaction with these models improves understanding and retention of relevant anatomical knowledge compared to traditional lectures. Researchers created six life-sized phantom heads with detachable mandibles—three exhibiting unilateral and three bilateral CLP—using MRI-based designs in ZBrush (Pixologic Inc., Los Angeles, CA, USA) and printed them on an Asiga Pro 4K 3D printer (Asiga, Sydney, Australia). Eighty-one students were split into two groups: the control group ($n = 39$) attended a conventional lecture on CLP, while the intervention group ($n = 42$) participated in an interactive session combining the same lecture with practical exercises using the 3D-printed models. Knowledge acquisition and self-confidence were measured before and after the sessions using multiple-choice tests and self-assessment questionnaires. Statistical analysis employed chi-square tests for item-level comparisons and Wilcoxon rank tests for overall knowledge gains, with $p < 0.05$ considered significant. Both the control and intervention groups exhibited significant improvements in knowledge and self-assessed competence following the sessions ($p < 0.001$). Notably, the intervention group demonstrated superior gains in understanding the anatomical features of unilateral CLP compared to the control group ($p < 0.05$). Incorporating 3D-printed CLP models into dental education enhances students' anatomical comprehension and engagement, demonstrating clear added value over traditional lecture-based teaching methods.

Keywords: Dental education, 3D printing, Cleft lip and palate, Prospective study, 3D rapid prototyping

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Introduction

Orthodontic education has evolved considerably due to technological innovations. Traditional lecture formats, such as chalkboard teaching, are increasingly being replaced with modern digital tools, which are now commonplace in subjects like anatomy, pathology, and embryology [1]. However, students frequently struggle to accurately perceive three-dimensional spatial relationships when relying exclusively on 2D images, limiting their grasp of complex anatomical structures. To overcome these limitations, educational strategies have begun incorporating immersive learning technologies, including 3D-printed models, augmented reality (AR), and virtual reality (VR), which provide more interactive and engaging ways to study [2].

Since the 1980s, when pioneers such as Masters, Hull, and Andre introduced additive manufacturing, 3D printing has expanded across diverse fields, from aerospace to healthcare. This technology enables the conversion of imaging data, such as CT or MRI scans, into physical models that can be touched, examined, and manipulated [3]. Advances in printing technologies and open-source software have made it feasible to produce accurate, cost-effective anatomical models suitable for surgical planning, patient communication, and teaching purposes. Recent studies highlight the educational advantages of 3D printing and immersive technologies like AR and VR in both medical and dental training [4].

Three-dimensional printed models offer unique benefits over traditional 2D resources. By allowing students to handle and inspect anatomical structures from multiple angles, these models enhance understanding of complex formations and procedural steps [5-7]. Practical engagement with such models also fosters teamwork, problem-solving, and critical thinking skills [8]. Tactile interaction with anatomical replicas provides learners with a more intuitive grasp of spatial relationships, a key competency for dental professionals [9, 10].

Teaching cleft lip and palate (CLP) in dental education presents specific challenges. Newborns with CLP are highly vulnerable, restricting opportunities for undergraduate students to participate in direct clinical care. Consequently, CLP education is largely theoretical, with limited hands-on practice, making it difficult for students to fully comprehend the anatomy and management of affected patients. The use of 3D-printed phantom heads and associated maxillary models offers a safe and interactive alternative, allowing students to practice and visualize procedures while reinforcing anatomical knowledge [10].

This study aimed to evaluate the impact of supplementing traditional CLP teaching with 3D-printed models on dental students' understanding and learning outcomes.

Materials and Methods

Study design and ethical approval

This prospective, single-center intervention study investigated whether incorporating 3D-printed models into the dental curriculum could improve students' comprehension of cleft lip and palate relative to standard lecture-based teaching. The study protocol was approved by the Ethics Committee of the Medical Faculty at J. W. Goethe University Frankfurt am Main (Approval No. 2023-1541, 16 November 2023), and written informed consent was obtained from all participants.

Participants and group allocation

Eighty-one fourth-year dental students were randomly allocated into two groups. The control group (CTR, n = 39) received a conventional lecture on cleft lip and palate using a PowerPoint presentation, whereas the intervention group (INT, n = 42) attended a hands-on seminar incorporating the same theoretical content alongside practical exercises with 3D-printed phantom heads displaying unilateral and bilateral CLP. Each phantom head was accompanied by a corresponding maxillary model and a custom-molded appliance, allowing students to simulate procedures safely. Participation was voluntary, and students could withdraw consent at any stage.

Randomization was performed electronically using Sealed Envelope™ (https://www.sealedenvelope.com/simple-randomiser/v1/lists, accessed 22 November 2023) with a 1:1 allocation ratio. The sequence was generated in advance, and students were assigned sequentially according to this pre-defined list. No physical envelopes or manual assignments were used. The study coordinator, who did not take part in teaching or assessments, conducted all allocations.

Inclusion criteria

Participants were limited to fourth-year dental students at J. W. Goethe University Frankfurt am Main who had little to no prior exposure to cleft lip and palate concepts and voluntarily agreed to take part in the study.

Exclusion criteria

Students were excluded if they were not enrolled in the dentistry program, belonged to a different academic year, opted out of participation, or already had advanced knowledge of CLP—for example, those engaged in CLP-related research projects, pursuing medical studies concurrently, or holding prior medical qualifications.

Sample size estimation

To determine the required number of participants, the study team collaborated with the Institute for Biostatistics and Mathematical Modeling at the Faculty of Medicine, J. W. Goethe University Frankfurt am Main, referencing

Kiesel *et al.* [11]. The calculation indicated that 74 students (37 per group) would provide sufficient power (≥80%) to detect an effect size of 0.7 in the primary outcome of student satisfaction, using a two-tailed, two-sample t-test at a 5 percent significance level. This estimate assumed a standard deviation of 1.06 and a mean difference of 0.7 between groups. Although slightly larger than that reported in the reference study, this difference remained within the corresponding confidence interval. Calculations were conducted using BiAS for Windows software, version 11.

Development of 3D models

Phantom heads

A total of six life-sized phantom heads were produced, comprising three models with unilateral CLP and three with bilateral CLP, using the CAD platform ZBrush (Maxon Computer GmbH, Bad Homburg, Germany, version 2023) **(Figure 1)**. The designs were based on MRI datasets representing both CLP types, providing highly detailed anatomical structures. The models were carefully crafted to replicate the distinct facial morphology characteristic of cleft conditions. Each phantom head incorporated a modular joint system, allowing the mandible to be detached and reattached easily, thereby enabling students to manipulate the models for practical exercises **(Figure 1)**.

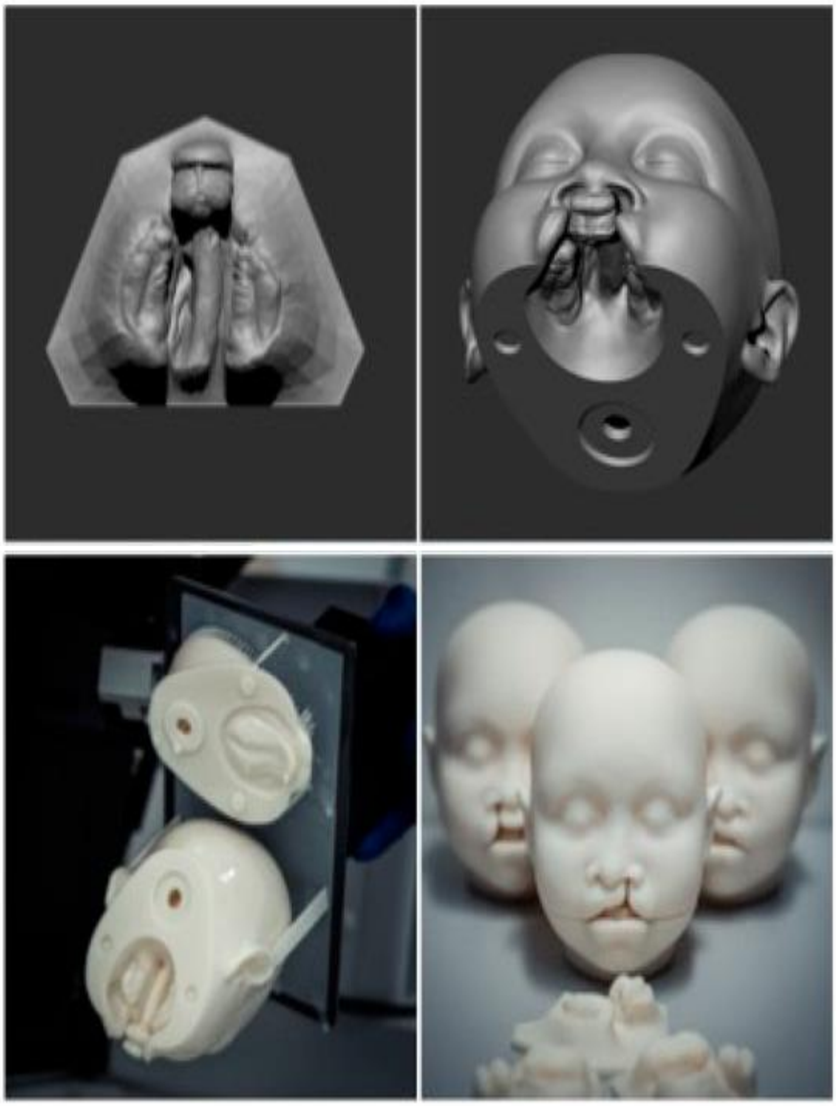


Figure 1. Clockwise: initial 3D scan of a bilateral CLP, digital phantom head with embedded intraoral scan, freshly printed upper and lower sections of the model, and the phantom head shown in three variations—bilateral CLP, left-sided CLP, and right-sided CLP

De-identified intraoral scans (IOSs) from routine CLP diagnostics, covering both unilateral and bilateral types, were incorporated into the digital 3D phantom head datasets. By removing the mandible, students could clearly view the cleft segments of the upper jaw, reproducing the exact morphology captured in the scans. Additionally, separate 3D-printed upper jaw models were produced from the same scan data to further aid visualization and study.

The digital models were exported as STL files and fabricated using a stereolithography (SLA) 3D printer (Asiga Pro 4K, Sydney, Australia), which builds objects layer by layer by curing liquid resin with UV light. After printing, the models underwent cleaning, surface refinement, and polishing to achieve realistic anatomical detail and smoothness.

Maxillary plates

Anonymized IOS data from CLP patients were also used to design feeding plates. Scan data were processed in OnyxCeph3TM (Image Instruments GmbH, Chemnitz, Germany; version 3.2.223) to generate digital dental models. Passive plates were designed in the software, exported for 3D printing, and fabricated using the Asiga Pro 4K printer. Post-processing included cleaning with isopropanol, UV curing, and final adjustments in the dental laboratory.

Active plates, which included functional elements like screws, were manufactured and polished in the in-house dental lab. All plates were precisely compatible with both the phantom heads and separately printed upper jaw models, ensuring accurate fit and realistic simulation for hands-on training **(Figure 2)**.

Figure 2. Top left: phantom head with unilateral cleft and inserted maxillary plate; top right: detached lower jaw section; bottom center: 3D-printed model of bilateral CLP fitted with the maxillary plate

Lecture content

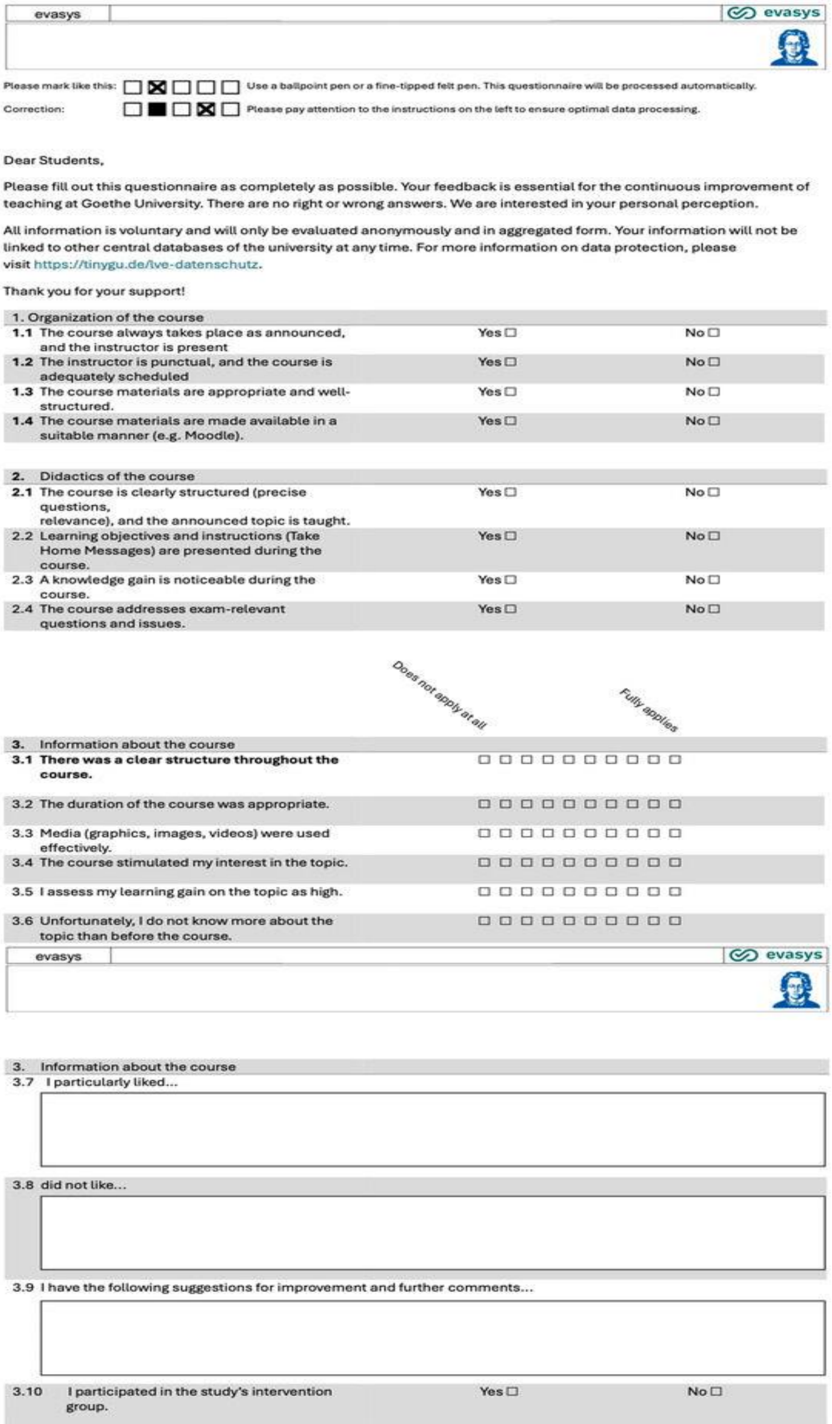
The seminar materials were identical for both groups. The lecture provided a structured overview of cleft lip and palate, including etiology, prevalence, and clinical presentation. Particular attention was given to the anatomy of CLP and the associated PSIO maxillary feeding plates. In the conventional lecture, these features were only presented digitally. During the hands-on seminar, however, students could handle 3D-printed phantom heads with integrated foam models, disassemble the head shells, and closely inspect the separated jaw segments. They could also place and remove the PSIO plates on the printed ridges, giving them a realistic tactile understanding of the anatomical structures and therapeutic devices.

Data collection

Eighty-one students were randomly allocated to two groups. The control group (CTR, n = 39) attended a traditional lecture delivered via PowerPoint, while the intervention group (INT, n = 42) participated in the same lecture supplemented with a practical session using 3D-printed phantom heads featuring unilateral and bilateral CLP along with their corresponding maxillary plates. Both groups received one hour of instruction by the same lecturer to ensure consistency.

To evaluate learning and satisfaction, all students completed three assessments: a course evaluation, a validated multiple-choice test (MCT), and a self-assessment questionnaire.

Course Evaluation: Immediately after the seminar, students filled out a structured evaluation form. This included yes/no items, 10-point Likert scales (1 = "Does not apply at all," 10 = "Fully applies"), and optional open-text responses for qualitative feedback. Only the numerical data were analyzed statistically, while written feedback provided additional context. The full evaluation is shown in **Figure 3**, with extra questions designed specifically for the INT group in **Figure 4**. The questionnaire was developed in collaboration with J. W. Goethe University Frankfurt am Main and administered online.



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Please mark like this: Use a ballpoint pen or a fine-tipped felt pen. This questionnaire will be processed automatically.

Correction: Please pay attention to the instructions on the left to ensure optimal data processing.

Dear Students,

Please fill out this questionnaire as completely as possible. Your feedback is essential for the continuous improvement of teaching at Goethe University. There are no right or wrong answers. We are interested in your personal perception.

All information is voluntary and will only be evaluated anonymously and in aggregated form. Your information will not be linked to other central databases of the university at any time. For more information on data protection, please visit https://tinygu.de/lve-datenschutz.

Thank you for your support!

1. Organization of the course		
1.1 The course always takes place as announced, and the instructor is present	Yes ☐	No ☐
1.2 The instructor is punctual, and the course is adequately scheduled	Yes ☐	No ☐
1.3 The course materials are appropriate and well-structured.	Yes ☐	No ☐
1.4 The course materials are made available in a suitable manner (e.g. Moodle).	Yes ☐	No ☐

2. Didactics of the course		
2.1 The course is clearly structured (precise questions, relevance), and the announced topic is taught.	Yes ☐	No ☐
2.2 Learning objectives and instructions (Take Home Messages) are presented during the course.	Yes ☐	No ☐
2.3 A knowledge gain is noticeable during the course.	Yes ☐	No ☐
2.4 The course addresses exam-relevant questions and issues.	Yes ☐	No ☐

3. Information about the course	Does not apply at all … Fully applies
3.1 There was a clear structure throughout the course.	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
3.2 The duration of the course was appropriate.	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
3.3 Media (graphics, images, videos) were used effectively.	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
3.4 The course stimulated my interest in the topic.	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
3.5 I assess my learning gain on the topic as high.	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
3.6 Unfortunately, I do not know more about the topic than before the course.	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐

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3. Information about the course

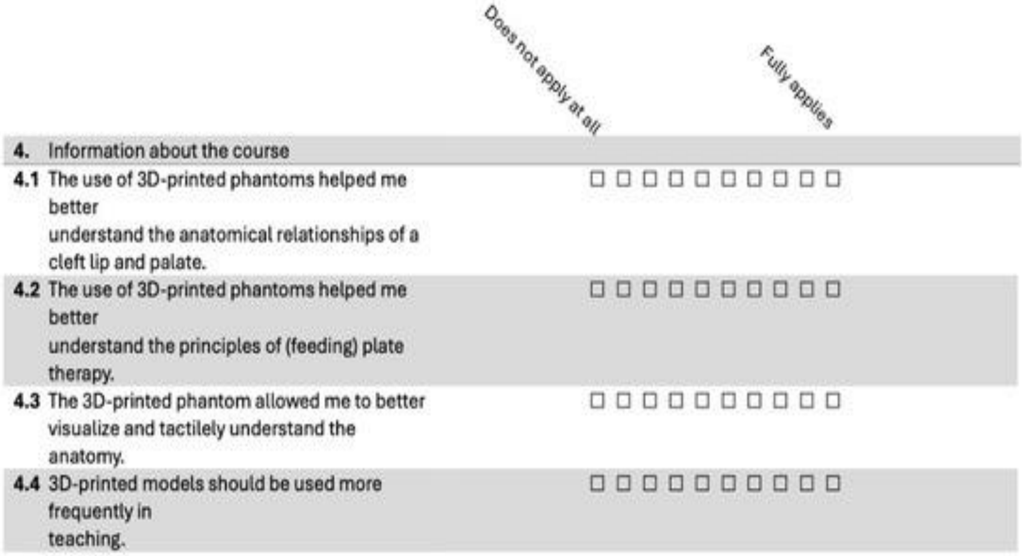
3.7 I particularly liked...

3.8 did not like...

3.9 I have the following suggestions for improvement and further comments...

3.10 I participated in the study's intervention group. Yes ☐ No ☐

Figure 3. Standard evaluation form used for evaluation of seminar by both groups


Does not apply at all | Fully applies

4.	**Information about the course**	
4.1	The use of 3D-printed phantoms helped me better understand the anatomical relationships of a cleft lip and palate.	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
4.2	The use of 3D-printed phantoms helped me better understand the principles of (feeding) plate therapy.	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
4.3	The 3D-printed phantom allowed me to better visualize and tactilely understand the anatomy.	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
4.4	3D-printed models should be used more frequently in teaching.	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐

Figure 4. Additional evaluation questions for the intervention group

Because only one instructor was responsible for conducting all instructional sessions and assessments, inter-rater reliability was not applicable in this study. However, to maintain consistency, a standardized script was used to guide lecture delivery and model demonstrations, ensuring that each group received identical instructional content and interaction.

To minimize potential assessment bias, outcome evaluations were performed under blinded conditions. The instructor who led both the control and intervention seminars did not take part in grading student performance. Instead, assessment papers were evaluated by independent examiners who were completely unaware of which instructional approach had been used (i.e., with or without 3D models), the students' group allocations, or the study's experimental objectives.

All post-seminar assessments were anonymized before grading, and no group identifiers or personal data were available to evaluators. This blinding protocol was implemented to ensure unbiased assessment and enhance the internal validity of the results.

Knowledge Questionnaire (MCT): A 14-item multiple-choice test (MCT) was administered before and after the seminar to evaluate participants' knowledge of cleft lip and palate (CLP). The items covered core topics such as anatomical structures, feeding plates, and early therapeutic interventions, allowing for a direct comparison of knowledge improvements between the control (CTR) and intervention (INT) groups.

The questionnaire was derived from the university's dental faculty's standardized internal question bank, which is routinely applied in official summative assessments and developed in accordance with the educational standards and learning objectives set by the German Ministry of Health and the university's academic board. Although formal psychometric validation was not performed, the questionnaire's design and content align with the recognized institutional and national educational frameworks.

Self-Assessment Questions: In addition, students completed five self-assessment items before and after the seminar (Section 3.3). These items evaluated their perceived understanding and interest in CLP, including awareness of CLP types, the value of interdisciplinary management, and the responsibilities of various specialists involved in CLP care. Responses were measured using a five-point Likert scale, ranging from "Strongly disagree" (1) to "Strongly agree" (5).

Statistical analysis

All statistical analyses were conducted under the direction of the Institute for Biostatistics and Mathematical Modeling, Faculty of Medicine, J. W. Goethe University Frankfurt am Main, using Jamovi version 2.3.28.0. Data normality was tested using the Shapiro–Wilk test to determine appropriate statistical methods. For datasets exhibiting normal distribution, paired t-tests were used to compare pre- and post-seminar results within each group, while the Wilcoxon signed-rank test served as the non-parametric alternative when normality assumptions were not met.

Three analytical components were included: (1) overall course evaluation, (2) analysis of the 14 knowledge questions, and (3) assessment of the five self-evaluation items regarding CLP knowledge and interest. Between-group comparisons (CTR vs. INT) for individual questions and self-assessment data were carried out using the Wilcoxon–Mann–Whitney U test. Descriptive statistics—mean (mv), median (md), and standard deviation (sd)—were calculated to summarize central tendency and dispersion.

A significance threshold of p = 0.05 was applied to all statistical tests. The entire analytical process adhered to recognized biostatistical standards, ensuring methodological rigor and reliability of the findings.

Results and Discussion

Students' satisfaction with the training seminar

According to the data presented in **Tables 1 and 2**, students in both the CTR and INT groups reported nearly equivalent levels of satisfaction with the seminar's structure and delivery. Evaluations indicated that participants rated all components—such as adherence to schedule, organization of content, appropriateness of materials, and overall course management—very highly. Notably, items like "The course takes place as announced, and the instructor is present" and "The course is clearly structured, and the announced topic is taught" yielded almost indistinguishable average scores, with only negligible variation in standard deviation between the two study groups.

Table 1. Evaluation of course organization by control (CTR) group and intervention (INT) group. mv = mean value; md = median; sd = standard deviation

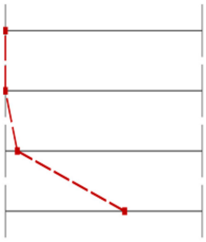
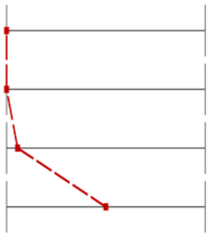
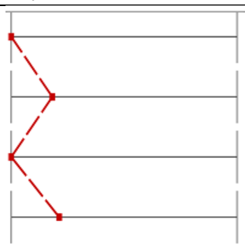
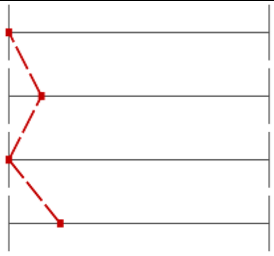
Organization of the Course	CTR (n = 33)					INT (n = 40)				
	yes	no	mv	md	sd	yes	no	mv	md	sd
The course takes place as announced, and the instructor is present			1.0	1.0	1.0			1.0	1.0	0.0
The instructor is punctual, and the course is adequately scheduled			1.0	1.0	0.0			1.0	1.0	0.0
The course materials are appropriate and well-structured			1.1	1.0	0.2			1.1	1.0	0.2
The course materials are made available in a suitable manner (e.g., Moodle)			1.6	2.0	0.5			1.4	1.0	0.5

Table 2. Evaluation of course didactics by control (CTR) group and intervention (INT) group. mv = mean value; md = median; sd = standard deviation

Didactics of the Course	CTR (n = 33)			INT (n = 40)		
	yes	no	mvmd sd	yes	no	mvmd sd
The course is clearly structured (precise questions, relevance), and the announced topic is taught.			1.01.00.0			1.01.00.0

Learning objectives and instructions (Take Home Messages) are presented during the course.	1.2 1.0 0.4		1.1 1.0 0.3
A knowledge gain is noticeable during the course.	1.0 1.0 0.0		1.0 1.0 0.0
The course addresses exam-relevant questions and issues.	1.2 1.0 0.4		1.2 1.0 0.4

Additional survey items specific to the 3D phantom experience were administered exclusively to the INT group, as illustrated in **Figure 5**.

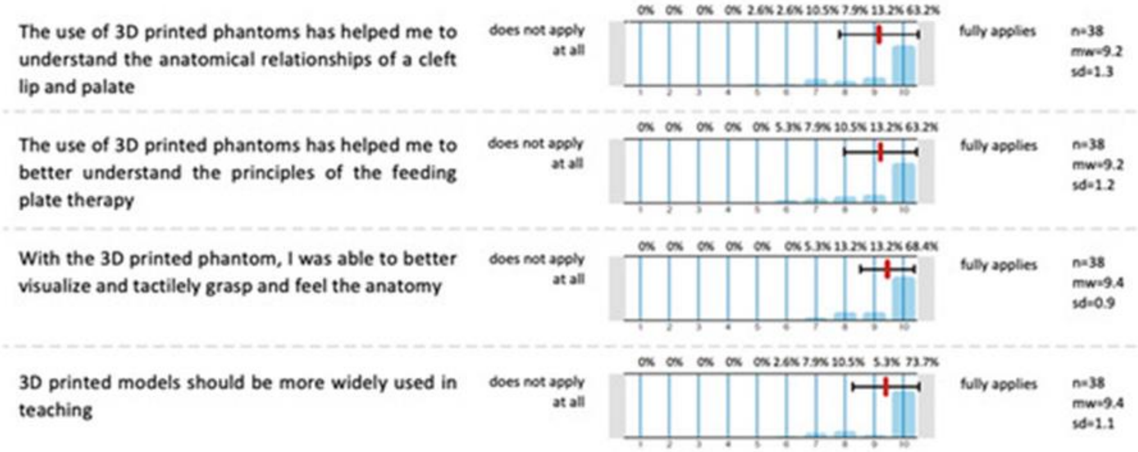


Figure 5. Self-assessment form including supplementary items for the INT group to appraise their experience with the 3D-printed phantoms. Responses were collected using a 10-point Likert scale (0 = Strongly disagree; 10 = Strongly agree); n = 38

Median values across all four items ranged from 9.2 to 9.4, with small standard deviations (0.9–1.3), signifying a consistent and highly positive perception among participants. Students reported that using the phantom heads substantially improved their grasp of anatomical relationships involved in cleft lip and palate (median = 9.2, SD = 1.3) and deepened their conceptual understanding of CLP plate therapy (median = 9.2, SD = 1.2). They also emphasized that the tactile and visual interaction with the models enhanced their spatial understanding of anatomical structures (median = 9.4, SD = 0.9). Furthermore, participants expressed strong approval for the expanded incorporation of 3D-printed phantoms into the teaching process (median = 9.4, SD = 1.1). Overall, these outcomes indicate that the application of 3D-printed models effectively strengthened learning outcomes and student satisfaction during the seminar.

Increase in knowledge

To assess knowledge development, students' understanding of cleft lip and palate was evaluated before and after the training using a 14-item multiple-choice test (MCT).

Table 3 presents the paired Wilcoxon test outcomes used to measure changes in the accuracy of responses for each question across both CTR and INT groups. Each question is listed with its corresponding Wilcoxon W statistic and p-value, reflecting whether post-seminar improvements were statistically significant. Both groups demonstrated significant gains on every individual question, as shown by p-values below 0.001. However, when overall performance was analyzed collectively ("Total" row), no statistically significant improvement was observed (p = 0.155 for CTR; p = 0.167 for INT). These findings suggest that although both groups improved notably on specific knowledge items following the seminar, this enhancement was not reflected in the total aggregated scores.

Table 3. Paired Wilcoxon test results for pre- and post-seminar improvements in knowledge questions

Group	Question (Pre- and Post-Seminar)	Wilcoxon W	p Value	Group	Question (Pre- and Post- Seminar)	Wilcoxon W	p Value
CTR	1	0.587	<0.001	INT	1	0.433	<0.001
	2	0.754	<0.001		2	0.738	<0.001
	3	0.789	<0.001		3	0.795	<0.001
	4	0.735	<0.001		4	0.739	<0.001
	5	0.693	<0.001		5	0.564	<0.001
	6	0.707	<0.001		6	0.757	<0.001
	7	0.611	<0.001		7	0.635	<0.001
	8	0.682	<0.001		8	0.497	<0.001
	9	0.797	<0.001		9	0.770	<0.001
	10	0.549	<0.001		10	0.683	<0.001
	11	0.698	<0.001		11	0.760	<0.001
	12	0.724	<0.001		12	0.740	<0.001
	13	0.677	<0.001		13	0.737	<0.001
	14	0.477	<0.001		14	0.502	<0.001
	Total	0.961	0.155		Total	0.959	0.167

The following analysis shifts focus from within-group progress to a direct comparison between the control (CTR) and intervention (INT) cohorts across all 14 knowledge test items. Notably, significant variation was detected only in Questions 9 and 10, suggesting that the inclusion of 3D-printed phantoms provided a measurable learning advantage for students in the INT group. In contrast, the remaining twelve questions displayed no meaningful statistical difference between the two cohorts.

As shown in **Figure 6**, Question 10—designed to assess comprehension of the distinct anatomical features seen in unilateral cleft lip and palate cases—revealed a clear performance gap, with the INT group achieving 40 correct answers compared to just 23 in the CTR group ($p < 0.001$, Wilcoxon test). Likewise, **Figure 7** demonstrates a similar trend for Question 9, which focused on the function and design of feeding plates in cleft care; here, INT participants recorded 21 correct responses, while the CTR group achieved only 9 ($p = 0.012$, Wilcoxon test).

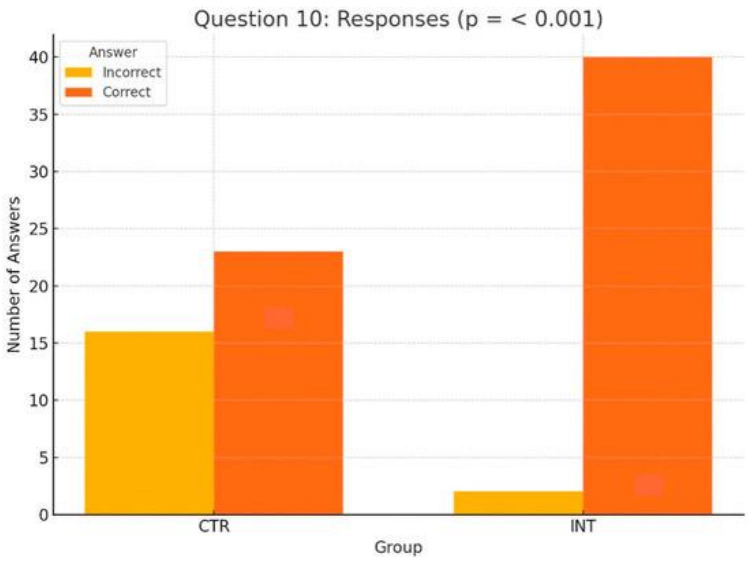


Figure 6. Comparison of correct versus incorrect answers for Question 10 (‘anatomical characteristics of a unilateral cleft lip’) between the CTR and INT groups ($p < 0.001$)

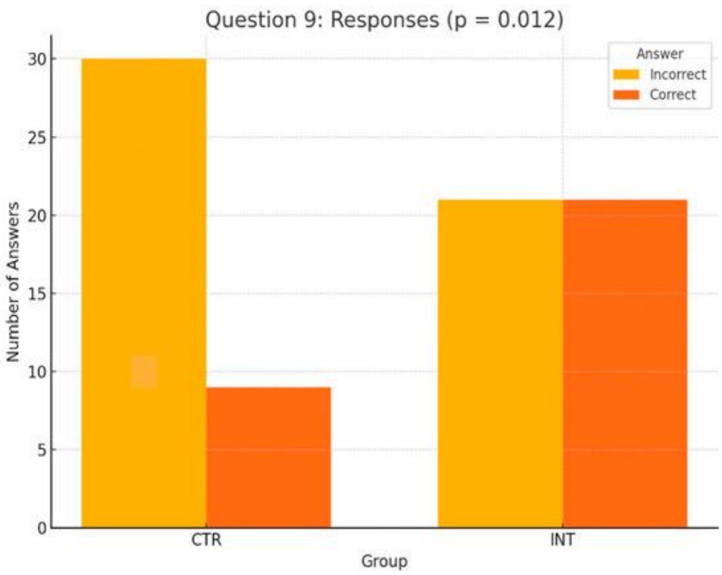


Figure 7. Correct versus incorrect responses for Question 9 ('feeding plate use in cleft lip and palate') are shown for the CTR and INT groups (p = 0.012)

Seminar-driven changes in self-evaluation: CTR compared with INT

Students rated their own understanding of and engagement with CLP both before and after attending the seminar, based on the items presented in **Table 4**. **Table 5** highlights that both groups experienced significant increases in scores for each individual question, as well as in the overall aggregate score, indicating measurable improvement following the seminar.

Table 4. Self-evaluation items on CLP knowledge and interest

Questions
(A) I feel confident about my understanding of cleft lip and palate.
(B) I have a strong interest in learning about cleft lip and palate.
(C) I am able to identify the various types of cleft lip and palate and describe how they differ.
(D) I can discuss why early treatment and a multidisciplinary approach are crucial in managing cleft lip and palate.
(E) I possess foundational knowledge of the contributions of speech therapists, orthodontists, and other specialists involved in CLP care.

Answer Options: Strongly agree (5), Agree (4), Neutral (3), Disagree (2), Strongly disagree (1).

Table 5. Pre- and post-seminar statistical results for self-assessment questions in CTR and INT groups

Group	**Question**	**W**	**p**	**Group**	**Question**	**W**	**p**
CTR	A	0.883	<0.001	INT	A	0.810	<0.001
	B	0.641	<0.001		B	0.522	<0.001
	C	0.871	<0.001		C	0.874	0.001
	D	0.851	<0.001		D	0.905	0.007
	E	0.861	<0.001		E	0.915	0.013
	All questions	0.748	<0.001		All questions	0.838	<0.001

In the CTR group, individual Wilcoxon W values ranged from 0.641 to 0.883, all with p-values under 0.001, indicating clear gains in students' self-perceived knowledge and interest after the seminar. When all questions were considered together, the overall W score was 0.748 ($p < 0.001$), confirming the seminar's positive effect on this group.

The INT group also demonstrated notable improvements, with W values spanning 0.522 to 0.915 and p-values between <0.001 and 0.013 for individual questions. The cumulative W for all items was 0.838 ($p < 0.001$). On several questions, including Question E, the INT group's W score (0.915) exceeded that of the CTR group (0.861), suggesting stronger perceived gains among students who used 3D-printed phantoms.

Both groups gave uniformly high ratings for all aspects of seminar delivery, indicating comparable evaluations of the organization and teaching quality. Therefore, differences in knowledge acquisition and topic comprehension are likely attributable to the inclusion of 3D-printed models in the INT group rather than variations in overall course quality. Students in the INT group reported that the tactile and visual experience provided by the 3D-printed phantoms improved their understanding of cleft anatomy and the use of presurgical plates. These observations are consistent with previous research showing that 3D models enhance engagement and anatomical comprehension in dental and surgical education [6,7, 10, 12–15]. Similarly, studies by Chen *et al.* and Chou *et al.* highlight that hands-on simulations improve both learning outcomes and communication with patients' families [13, 16].

Knowledge of CLP was assessed using a 14-item multiple-choice test administered before and after the seminar. While both groups demonstrated significant improvements for individual items, overall combined scores did not show a statistically significant change. Nevertheless, post-seminar performance on each question improved significantly in both groups. This aligns with Dalgalı *et al.* [17], who reported that short-term test scores benefit from 3D-model-assisted learning, although long-term differences between teaching approaches are limited. These findings reinforce that physical models are effective in supporting understanding of specific topics, but consistent reinforcement may be needed to achieve broad knowledge retention [10, 13, 17].

Examining pre- and post-seminar performance between groups, significant differences emerged for Questions 9 and 10, demonstrating the educational advantage of 3D-printed phantoms. For Question 10, which addressed the anatomy of a unilateral cleft lip and palate, the INT group outperformed the CTR group ($p < 0.001$). For Question 9, focusing on maxillary feeding plates, the INT group recorded 21 correct responses compared to 9 in the CTR group ($p = 0.012$). These findings underscore the value of hands-on 3D models in facilitating comprehension of complex anatomical structures and presurgical procedures. The remaining 12 questions showed no significant differences, consistent with prior studies indicating that 3D models most strongly enhance spatial understanding and procedural knowledge [10,13–15]. Research by Teuber Lobos *et al.* and Wright *et al.* further supports that cleft simulation models substantially improve anatomical recognition and surgical planning skills [14, 15].

Students' self-evaluations of their knowledge and interest in cleft lip and palate (CLP) demonstrated clear improvements following the seminar. Both the CTR and INT groups showed statistically significant gains on each question and in the overall combined scores. However, the INT group—who engaged with 3D-printed phantoms—consistently achieved higher Wilcoxon W values for several items, indicating more pronounced perceived progress. These findings highlight the seminar's effectiveness in enhancing learners' confidence and interest, while also illustrating the additional benefits of hands-on, model-based learning. In line with Chou *et al.* [16], the use of tactile simulation tools not only strengthened students' understanding but also improved their ability to communicate complex concepts to patients' families. This suggests that 3D models can enhance both cognitive and affective aspects of learner-centered clinical education, including perceived competence and engagement [10, 13, 16].

Although exposure to 3D models improved scores on select questions—particularly those requiring anatomical or spatial reasoning—overall test scores did not differ significantly between the groups. This pattern reflects findings from Dalgalı *et al.* [17], who observed that 3D-assisted learning enhances short-term knowledge acquisition without guaranteeing long-term retention. The results point to the importance of instructional design: core topics such as etiology or epidemiology may be better conveyed through lectures and visual aids, whereas 3D models are particularly suited to developing spatial understanding and hands-on skills [1, 6, 10, 12]. Notably, learners in the INT group reported higher engagement and satisfaction, echoing outcomes from other studies that employed hands-on 3D tools in dental education [7, 8, 10].

The use of additive manufacturing has rapidly expanded beyond healthcare into industries such as aerospace, architecture, and automotive design, and its educational applications are similarly growing. Advanced digital technologies now allow imaging data from CT or MRI scans to be transformed into tangible, high-fidelity models [3]. A wide variety of 3D printing platforms and open-source software enable the creation of accurate and affordable anatomical models, which are increasingly integrated into medical education for purposes ranging from surgical planning to patient education and classroom training. Such models have been applied to the heart, face, bones, eyes, arteries, pelvis, liver, chest, and skull, supporting both practical skills development and conceptual learning [4, 12].

The use of three-dimensional (3D) printed anatomical models is becoming increasingly prominent in dental education because they provide a more immersive and interactive learning experience than traditional textbooks. Unlike flat, two-dimensional images, these models allow students to observe anatomical structures from multiple perspectives, which improves comprehension of complex spatial relationships [5-7]. Incorporating these models into hands-on lectures also fosters problem-solving skills and encourages collaboration among learners [8]. By offering tactile interaction, 3D models enhance students' ability to visualize structures accurately and examine pathologies from different angles—a crucial competency for future dental professionals [9, 10].

In one study, Seifert *et al.* [6] compared learning outcomes for dental students using 3D-printed, patient-specific models versus traditional cadaveric specimens across several procedures, including mucoperiosteal flap dissection, third-molar osteotomy, free-mucosal-graft dissection, and root tip resection. Although cadavers provided better soft-tissue feedback, the 3D-printed models scored higher for anatomical precision, simulation realism, and range of motion. Similarly, Richter *et al.* [7] examined the use of 3D-printed tooth models in a conservative dentistry course with thirteen dentists and twenty-seven students. Participants carried out caries removal, cavity preparation, and restorations, rating the 3D-printed models as more realistic in terms of tactile sensation and color differentiation, while also being more cost-effective than commercial alternatives.

For cleft lip and palate (CLP) education, 3D-printed models have mainly been used to teach surgical techniques within oral and maxillofacial programs. Chen *et al.* [13] demonstrated that a silicone cleft lip simulation model increased trainees' confidence in surgical procedures and anatomical landmark recognition compared with a conventional lecture-based approach. Wright *et al.* [14] validated a craniofacial model for fronto-orbital advancement, finding that simulations significantly improved junior residents' knowledge scores. Likewise, Teuber Lobos *et al.* [15] found hybrid CLP models to be effective teaching tools for both novice and experienced surgeons, while Chou *et al.* [16] showed that such models also enhance parental understanding of their child's condition before surgery.

In orthodontic education, the adoption of 3D-printed phantoms for CLP training is emerging but remains underexplored. AlAli *et al.* [10] reported that seminars using 3D-printed models significantly increased participants' knowledge, with intervention groups outperforming controls on post-seminar assessments. Similar to our findings, this study highlighted the learning benefits of hands-on models; however, unlike our results, AlAli *et al.* also observed higher participant satisfaction in the intervention group compared to controls.

Our study primarily assessed immediate learning outcomes, as knowledge was evaluated on the same day before and after the seminar. In comparison, Dalgali *et al.* [17] examined the effectiveness of 3D-printed dental models and e-learning in CLP education across three different time points. They found that participants using 3D-printed models performed better in short-term assessments than those using e-learning alone. However, in contrast to our findings, their study reported no significant differences compared with baseline scores immediately post-training. Moreover, no differences between methods were observed during follow-up assessments at one week and one month, highlighting the need for future research on long-term retention in orthodontic education. Considering that 3D-printed CLP phantoms are both realistic and cost-efficient, further studies investigating their sustained impact on learning outcomes are warranted.

This study demonstrates the value of hands-on educational tools, particularly 3D-printed phantoms, in helping students grasp complex anatomical structures and presurgical maxillary plate procedures. Data from the INT group suggest that incorporating these models into teaching not only supports understanding but also enhances student satisfaction. Such findings advocate for the broader adoption of 3D-printed phantoms in orthodontic training, potentially establishing a new standard for teaching challenging anatomical and pathological concepts like those related to cleft lip and palate.

Limitations

Several limitations should be considered. Despite having the same instructor lead both control and intervention sessions to reduce variability, the small sample size and inclusion of participants from a single university limit the generalizability of results. Additionally, while the questionnaire was drawn from the university's standardized exam pool and aligned with national learning objectives, it has not undergone formal psychometric validation, restricting external validity and measurement precision. The study's short-term design also limits conclusions about long-term knowledge retention; repeated assessments over extended periods would be needed to address this. Finally, the per-protocol analysis approach introduces a potential for bias in the results.

Conclusion

Our findings indicate that 3D-printed anatomical models can increase student engagement and facilitate comprehension of complex CLP-related content. Nevertheless, these results should be interpreted with caution due to the study's limited scope, single-institution setting, and small sample size. As curricular structures and teaching strategies vary across dental schools, the general applicability of these outcomes remains uncertain. Despite these constraints, 3D-printed models appear to offer a valuable supplement to conventional teaching methods, providing a hands-on approach that may deepen learning and understanding in targeted areas of dental education.

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