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Effectiveness of a Virtual Simulation Teaching System for Dental Wax Pattern Fabrication: A Pilot Crossover Study

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Abstract

Background

Dental wax pattern fabrication is a core skill in dental technology education, but traditional teaching suffers from high resource consumption, limited individualized guidance, and delayed feedback. Virtual simulation technology offers new possibilities for skill training. This pilot study aimed to develop a virtual simulation teaching system for dental wax pattern fabrication and preliminarily explore its feasibility and potential effectiveness through a crossover design.

Methods

Fourteen undergraduate volunteers from the Dental Technology program were randomly assigned to a physical-first group (n = 7) or a virtual-first group (n = 7). The physical-first group received traditional physical model training first, followed by virtual simulation training, while the virtual-first group received the opposite. Both groups underwent progressive training on the right maxillary central incisor, canine, first premolar, and first molar over 4 weeks, with the right maxillary first molar as the final assessment tooth. Operation skill scores, practice time, and user satisfaction were compared using independent t-tests, paired t-tests, repeated measures ANOVA, and ANCOVA.

Results

After the first stage, the virtual-first group scored 87.14 ± 7.56 on the virtual system, while the physical-first group scored 83.57 ± 17.39 on physical models ($P > 0.05$). After switching, the virtual-first group achieved significantly higher physical model scores (95.00 ± 7.64) than the physical-first group's virtual system scores (75.29 ± 12.97) ($t = 3.465$, $P = 0.005$). ANCOVA showed adjusted means of 79.807 and 79.050 ($P > 0.05$), indicating equivalent net effects. The virtual-first group spent significantly less time on all tooth positions ($P < 0.01$), with molar time reduced by over 70% (13.22 ± 3.62 vs. 44.15 ± 12.81 minutes). User satisfaction was high: 86.67% rated platform smoothness positively, 86.67% approved realistic simulation, and 93.33% agreed the platform should be introduced into traditional classrooms.

Conclusions

This pilot study provides preliminary evidence that the virtual simulation teaching system may improve learning efficiency and provide standardized training for dental wax pattern education. These findings support the feasibility of the "virtual-first → physical consolidation" blended model and lay the groundwork for future large-scale, multicenter studies to validate its effectiveness.

1. Introduction

Dental wax pattern fabrication is a fundamental skill in dental technology education, serving as a bridge between theoretical knowledge of tooth morphology and clinical restorative practice [1]. Mastering this skill requires not only a solid understanding of dental anatomy but also repeated practice to develop three-dimensional spatial perception, hand-eye coordination, and fine motor control [2].

Traditional wax pattern teaching relies heavily on the master-apprentice model in physical laboratories, where students practice on plaster models with wax and teachers provide observation-based guidance. While this model has played an important role in skill transmission, its limitations are increasingly evident: high consumption of teaching resources, difficulty in covering all students with individualized guidance, irreversible operations, and delayed subjective feedback [3, 4].

With the integration of digital technology and medical education, virtual simulation has emerged as a powerful tool for innovating traditional skill training models [5]. Virtual simulation systems create highly realistic three-dimensional interactive environments, enabling learners to practice skills in risk-free, low-consumption, repeatable virtual scenarios [6]. These technologies have demonstrated significant advantages in surgery, nursing, and dental education [7]. In dental teaching, virtual simulation has been applied to tooth preparation, implant planning, and local anesthesia training [8–10]. However, systematic development and validation of virtual simulation systems for wax pattern fabrication—a core skill requiring precise operation and spatial perception—remain limited [11].

The educational value of virtual simulation systems ultimately requires empirical validation of teaching effectiveness [12]. Wang et al. [13] developed a dental implant virtual simulation system that significantly improved trainees' operational proficiency, while Pham et al. [14]build a tooth preparation training platform that reduced student error rates by 35% through real-time feedback mechanisms. These studies provide strong empirical support for virtual simulation in dental skills training and offer methodological references for validating wax pattern virtual simulation systems.

As a pilot study, this research aimed to preliminarily explore the feasibility and potential effectiveness of a self-developed virtual simulation teaching system for dental wax pattern fabrication. Through a crossover design, we sought to obtain initial data comparing the virtual simulation training mode with traditional physical model training across multiple dimensions: operational skill scores, practice time, learning satisfaction, and system usability. The findings of this pilot study are intended to provide foundational data and inform the design of future large-scale, multicenter investigations to validate the efficacy of this educational approach.

2. Materials and Methods

2.1 Participants

Fourteen undergraduate volunteers from the Dental Technology program at Binzhou Medical University were enrolled. Inclusion criteria: (1) completed theoretical study of Oral Anatomy and Physiology, with basic knowledge of tooth morphology; (2) no prior exposure to any wax pattern virtual simulation

teaching system; (3) voluntary participation with informed consent. Exclusion criteria: (1) previous training with other virtual simulation systems for wax pattern fabrication; (2) inability to complete virtual operations due to physical conditions (e.g., color vision abnormalities, hand motor dysfunction); (3) inability to complete the full experimental cycle.

2.2 Experimental Design

A crossover design was adopted. Volunteers were randomly assigned to two groups using a random number table (Table 1).

Physical-first group (n = 7)

Volunteers first trained with traditional physical models, then received supplementary training with the virtual simulation system.

Virtual-first group (n = 7)

Volunteers first trained with the wax pattern virtual simulation system, then consolidated skills with traditional physical models.

Both groups alternated training sessions during the same period, ensuring consistent total training time, content, and guidance frequency.

Table 1
Baseline characteristics of participants

Characteristics	Physical-first (n = 7)	Virtual-first (n = 7)
Gender (Female/Male)	5/2	4/3
Age (years)	20.57 ± 0.98	20.57 ± 0.79

Training proceeded in order of increasing anatomical complexity: right maxillary central incisor (week 1) → right maxillary canine (week 2) → right maxillary first premolar (week 3) → right maxillary first molar (week 4). The final assessment tooth was the right maxillary first molar, which has the most complex cusp morphology, fossa system, and occlusal relationships, comprehensively testing volunteers' application of dental anatomy knowledge and refined operation skills.

2.3 Virtual Simulation Teaching System

The virtual simulation teaching system was developed based on the Unity3D engine (Unity Technologies, USA). High-precision three-dimensional models of dental anatomy, wax pattern tools, and virtual scenes were constructed using Maya (Autodesk, USA) and Solidworks (Dassault Systèmes, USA). The system architecture followed a layered design principle, integrating four functional modules: 3D scene and model library, physical interaction and behavior simulation, user interaction and interface, and intelligent evaluation and feedback. The model surfaces were optimized through polygon reduction and format

conversion to ensure smooth rendering in Unity3D. Collision detection technology based on Unity's PhysX engine was employed to simulate the plastic deformation of wax materials during the molding process, providing real-time interactive feedback.

2.4 Evaluation Indicators

2.4.1 Operational Skill Scores

Operational skill was evaluated using both physical model scoring and virtual system scoring, with physical model scoring as the main evaluation of the final skill level.Physical model scores (0-100) were assigned by one teacher of Prosthodontics with > 10 years' experience using double-blind independent scoring according to a standardized scoring form (Table 2).A calibration process was conducted prior to the formal assessment, with the teacher scoring five pilot samples twice (two-week interval), demonstrating excellent intra-rater reliability (ICC = 0.94,95%CI: 0.89–0.97).

Table 2
Scoring form for tooth wax pattern build-up operation

Item	Scoring criteria	Score
Instrument preparation	Models, carving knives (large/small), pen, ruler, wax blocks	5
Operation process	Proficient use of instruments and materials in proper sequence within time limit	8
Operation time	60 minutes	10
Operation results	Labial/buccal surface (8), lingual surface (8), mesial surface (5), distal surface (5), incisal/occlusal surface (8), mesio-buccal (labial) axial angle (5), disto-buccal (labial) axial angle (5), mesio-lingual axial angle (5), disto-lingual axial angle (5), cervical margin (5), occlusion (8), surface anatomical features (5), detail manifestation (5)	74
Total		100

Virtual system scores (0-100) were automatically generated by the built-in algorithm as auxiliary evaluation indicators (Table 3).

Table 3
Virtual system evaluation dimensions

Dimension	Full score
Initial wax layer formation	5
Proximal contact formation	10
Contact area formation	20
Occlusal surface boundary formation	20
Buccal surface buildup	5
Lingual surface buildup	5
Occlusal surface completion	35

Skill tests were conducted at different stages according to the crossover design (Table 4).

Table 4
Skill test schedule

Time point	Physical-first group	Virtual-first group
Pre-training	Physical model score	Physical model score
After stage 1	Physical model score	Virtual system score
After stage 2	Virtual system score	Physical model score

2.4.2 Practice Time

Practice time for each tooth position was recorded as the core indicator of training efficiency. Time limit per tooth was 60 minutes. Actual time was recorded if ≤ 60 minutes; otherwise, recorded as 60 minutes.

2.4.3 Learning Satisfaction and System Usability

A self-administered questionnaire was developed covering system performance, learning experience, and willingness to adopt, using a 5-point Likert scale.The self-administered questionnaire consisted of 12 items covering three dimensions: system performance and usability (4 items), learning experience and effectiveness (6 items), and acceptance and willingness to adopt (2 items). Each item was rated on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The detailed questionnaire items are provided in the Supplementary Materials.

2.5 Statistical Analysis

SPSS 26.0 was used for statistical analysis, with graphs generated using Prism 9.4. Data normality was tested with Shapiro-Wilk test and homogeneity of variance with Levene's test. Independent t-tests or Mann-Whitney U tests were used for between-group comparisons. Paired t-tests or Wilcoxon signed-rank tests were used for within-group comparisons. ANCOVA was used to compare post-test scores with pre-

test scores as covariate. Repeated measures ANOVA with Bonferroni correction was used for trend analysis of practice time across tooth positions. Significance level was set at $P < 0.05$.

3. Results

3.1 Operational Skill Scores

Baseline characteristics showed no significant differences between groups in age, gender, or pre-training physical model scores ($P > 0.05$), indicating comparability (Table 1).

Table 5
Comparison of skill scores after stage 1

	Group (Mean ± SD)		t	P
	Physical-first (n = 7)	Virtual-first (n = 7)		
Skill score	83.57 ± 17.39	87.14 ± 7.56	-0.498	0.627

After stage 1, the physical-first group scored 83.57 ± 17.39 on physical models, while the virtual-first group scored 87.14 ± 7.56 on the virtual system, with no significant difference ($P > 0.05$). Notably, the physical-first group had a larger standard deviation (17.39), indicating greater individual variability under traditional training, while the virtual-first group's smaller standard deviation (7.56) reflected more homogeneous training effect(Table 5).

Table 6
Comparison of skill scores after stage 2

	Group (Mean ± SD)		t	P
	Physical-first (n = 7)	Virtual-first (n = 7)		
Skill score	95.00 ± 7.64	75.29 ± 12.97	3.465	0.005**

After stage 2, the virtual-first group achieved significantly higher physical model scores (95.00 ± 7.64) than the physical-first group's virtual system scores (75.29 ± 12.97) ($t = 3.465$, $P = 0.005$) (Table 6).The effect size for this difference was large (Cohen's $d = 1.85$). This indicates that volunteers following the "virtual-first" sequence developed a solid foundation in tooth morphology cognition and operation specification, which was effectively consolidated through subsequent physical training,ultimately achieving a high score of 95.0.

Table 7
Pre-post comparison within groups

Group	Item	Mean	SD	Mean difference	t	P
Physical-first	Pre-training	76.43	13.78	-7.14	-1.622	0.156
	Post-stage 1	83.57	17.39			
Virtual-first	Pre-training	66.00	19.46	-9.29	-2.709	0.035*
	Post-stage 1	75.29	12.97			

Paired t-tests showed that the physical-first group's improvement (76.43 ± 13.78 → 83.57 ± 17.39, + 7.14) was not significant (P = 0.156), while the virtual-first group's improvement (66.00 ± 19.46 → 75.29 ± 12.97, + 9.29) was significant (P = 0.035) (Table 7). The effect size for this improvement was large (Cohen's d = 0.97).The virtual-first group's post-training standard deviation decreased markedly (19.46→12.97), indicating that the virtual simulation system provided a standardized, homogeneous training environment that effectively reduced individual differences among learners.

Table 8
ANCOVA of final physical model skill scores

Source	SS	df	MS	F	P
Corrected model	2018.77	2	1009.39	10.63	0.003**
Pre-training score	1778.48	1	1778.48	18.73	0.001**
Group	1.76	1	1.76	0.019	0.894
Error	1044.64	11	94.97		

ANCOVA with pre-training score as covariate showed that pre-training score had a significant effect on final score (F = 18.73, P = 0.001), while group effect was not significant (F = 0.019, P = 0.894) (Table 8). Adjusted means were 79.807 for the physical-first group and 79.050 for the virtual-first group, differing by only 0.757 points (P > 0.05), indicating equivalent net effects of the two training modes.

3.2 Practice Time Analysis

First-stage practice times were analyzed as they best reflected the original learning efficiency of each training mode, uncontaminated by prior experience.

Table 9
Comparison of practice time per tooth (minutes)

Tooth position	Physical-first (n = 7)	Virtual-first (n = 7)	t	P
Central incisor	23.46 ± 8.25	5.77 ± 0.90	5.641	0.001**
Canine	25.71 ± 6.19	8.10 ± 1.30	7.371	< 0.001**
First premolar	27.59 ± 7.28	8.92 ± 1.82	6.584	< 0.001**
First molar	44.15 ± 12.81	13.22 ± 3.62	6.148	< 0.001**

The virtual-first group spent significantly less time on all four tooth positions (P < 0.01), with molar time reduced by over 70% (13.22 ± 3.62 vs. 44.15 ± 12.81 minutes) (Table 9). The effect sizes for these differences were large, with Cohen's d values of 2.98 for central incisor, 3.89 for canine, 3.48 for first premolar, and 3.25 for first molar.The physical-first group's standard deviations were consistently larger (e.g., molar: 12.81 vs. 3.62), reflecting greater individual variability under traditional training, while the virtual simulation system provided more homogeneous training effects.

Table 10
Estimated marginal means of practice time (minutes)

Group	Central incisor	Canine	First premolar	First molar
Physical-first	23.46	25.71	27.59	44.15
Virtual-first	5.77	8.10	8.92	13.22

Repeated measures ANOVA showed significant effects of tooth position (F = 19.315, P < 0.001) and tooth position × group interaction (F = 5.241, P = 0.013). The virtual-first group showed smoother time increases across adjacent tooth positions (all P < 0.05), indicating more systematic adaptation to progressively increasingly difficult learning pace, while the physical-first group showed sharp time increases at the molar stage (Table 10, Fig. 1).

3.3 System Usability and User Experience

The questionnaire showed good reliability (Cronbach's α = 0.916) and validity (cumulative variance explained 95.36%).

System performance

86.67% of users rated platform smoothness as satisfied or very satisfied (66.67% very satisfied); 86.67% approve realistic simulation of instrument hand feeling and wax visual effect(mean score 4.4/5); over 85% were satisfied with system stability; 80% were very satisfied with interface design (20% satisfied, no negative evaluations).

Learning experience

73.33% were very satisfied with learning interest motivate; 100% affirmed the platform's assist in understanding steps and previewing/reviewing (73.33% very satisfied); 80% were very satisfied with improved 3D spatial perception (mean 4.73/5); 100% were satisfied with deepened understanding of dental anatomy (80% very satisfied); 80% were very satisfied with improved operational accuracy; 66.67% were very satisfied with improved learning efficiency (100% satisfied overall).

Acceptance and willingness to adopt

53.33% were very willing to continue using the platform after class, 26.67% willing; 93.33% agreed that the platform should be introduced into traditional classrooms as an auxiliary teaching tools (Fig. 2).

4. Discussion

This pilot study provides preliminary evidence for the feasibility and potential effectiveness of a virtual simulation teaching system for dental wax pattern fabrication through a crossover design, yielding several notable findings. These findings are consistent with previous research on virtual simulation applications in dental education. Zheng et al. [8] reported that the DentSim virtual dental teaching system reduced teacher-student interaction time by 60% and saved 83% of time per student in preclinical training. Similarly, Collaco et al. [18] demonstrated that a virtual reality training system for inferior alveolar nerve block achieved 84% accuracy in providing real-time feedback on needle insertion points. Together, these studies support the effectiveness of virtual simulation in improving dental skill acquisition and reducing training time.

The virtual-first group spent significantly less time on all tooth positions, with molar time reduced by over 70% (13.22 ± 3.62 vs. 44.15 ± 12.81 minutes, $P < 0.01$). This demonstrates the substantial advantage of virtual simulation training in learning efficiency, particularly for complex posterior teeth. This finding aligns with Ren et al. [15], who reported that virtual reality-based dental skill training systems significantly reduce operation time and improve learning efficiency. The real-time guidance,visual feedback, and standardized operation demonstration provided by virtual simulation systems help learners master key points more quickly, reducing ineffective attempts and errors.

Within-group comparisons showed significant improvement in the virtual-first group (66.00 ± 19.46 → 75.29 ± 12.97, $P = 0.035$), with post-training standard deviation decreasing markedly, indicating that virtual simulation provides a standardized, homogeneous training environment that effectively reduces individual differences. ANCOVA confirmed equivalent net effects of the two training modes after adjusting for baseline differences, suggesting that training sequence does not decisively influence final skill level. This finding is consistent with Alnahhal et al. [16], who found that virtual simulation systems with standardized operation procedure and instant feedback mechanism help learners with different starting points achieve comparable skill levels.

User experience data strongly support the platform's value: 86.67% rated platform smoothness positively, 86.67% approve realistic simulation, and 93.33% agreed the platform should be introduced

into traditional classrooms. The high degree of satisfaction in learning interest (73.33% very satisfied), 3D spatial perception (80% very satisfied), and deepened anatomical understanding (100% satisfied) confirms that virtual simulation systems effectively transform abstract concepts into concrete cognition, addressing the traditional challenge of translating 2D diagrams into 3D morphological understanding [17].Interestingly, the virtual-first group scored higher on their first virtual assessment (87.14 ± 7.56) than the physical-first group on their second virtual assessment (75.29 ± 12.97), despite having no prior experience with the system. This suggests that the virtual simulation system is particularly effective for novice learners, providing an intuitive and accessible entry point for skill acquisition.

The significant tooth position × group interaction ($F = 5.241$, $P = 0.013$) in practice time trends reveals that virtual simulation helps learners adapt more systematically to progressively increasingly difficult learning pace, while traditional training leads to sharp time increases at complex stages. This smooth learning curve likely contributes to the more homogeneous outcomes observed in the virtual-first group.

This study has several limitations that should be acknowledged. First, as a pilot study, the sample size ($n = 14$) was relatively small, which is typical for exploratory investigations aimed at generating preliminary data. While this may limit the statistical power and generalizability of the findings, the effect sizes observed (e.g., 70% reduction in practice time, Partial $\eta^2=0.72$) suggest meaningful educational benefits that warrant further investigation. Future multicenter studies with larger sample sizes are needed to validate these results.

The effectiveness of the virtual simulation system can be attributed to its alignment with constructivist learning theory, which posits that learners actively construct knowledge through exploration and practice rather than passively receiving information [19]. In the virtual environment, students were able to freely explore, repeatedly attempt, and learn from mistakes, with the teacher serving as a guide rather than a knowledge transmitter. This learner-centered approach likely contributed to the observed improvements in learning efficiency and skill acquisition.However, achieving high-fidelity physical simulation of wax material deformation remains technically challenging, particularly in balancing computational efficiency with anatomical accuracy. Future development should focus on optimizing finite element models and mesh processing algorithms to enhance real-time performance while preserving detailed morphological features [20].

Based on these findings, several practical implications for dental education can be drawn. First, the "virtual-first → physical consolidation" blended model can serve as an optimal path for wax pattern skill training, ensuring learning efficiency while building solid skill foundations. Second, virtual simulation systems can effectively supplement traditional physical training, particularly for complex posterior teeth. Third, virtual simulation provides standardized training environments that reduce individual differences and improve overall teaching quality.

5. Conclusions

This pilot study demonstrates the feasibility of using a virtual simulation teaching system for dental wax pattern fabrication and provides preliminary evidence of its potential benefits in dental technology education. The virtual-first group showed promising results, including a 70% reduction in practice time on complex tooth positions (13.22 ± 3.62 vs. 44.15 ± 12.81 minutes), higher final skill scores (95.00 ± 7.64), and more homogeneous training outcomes (standard deviation decreased from 19.46 to 12.97). User satisfaction was encouraging, with 93.33% of participants agreeing that the platform should be introduced into traditional classrooms, and high satisfaction rates observed for learning interest (73.33% very satisfied), 3D spatial perception (80% very satisfied), and anatomical understanding (100% satisfied).

These preliminary findings suggest that virtual simulation technology may enhance learning efficiency, provide standardized training, and improve spatial perception and anatomical understanding in dental wax pattern education. The "virtual-first → physical consolidation" blended model appears to be a promising approach for dental technology programs. However, as this is a pilot study with a limited sample size, these results should be interpreted with caution. Future large-scale, multicenter studies are warranted to confirm these findings and further validate the effectiveness of this educational approach. This study provides foundational data and valuable insights for the continued development and implementation of virtual simulation technology in dental education.

Declarations

Ethics approval and consent to participate:

Clinical trial number: Not applicable. This study was conducted in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments. The study protocol was reviewed and approved by the Ethics Committee of Yantai Stomatological Hospital of Binzhou Medical University (Approval No. 202603006). All participants were informed about the purpose and procedures of the study, and written informed consent was obtained from all individual participants prior to the commencement of the training.

Consent for publication:

Not applicable. This manuscript does not contain any individual person’s data, images, or other identifiable information.

Informed Consent

Statement:All participants were informed about the purpose and procedures of the study, and written informed consent was obtained from all individual participants included in the study prior to the commencement of the training.

Conflicts of Interest:

The authors declare no conflicts of interest.

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Author Contribution

Conceptualization, SU Qilong and REN Guanghui.; methodology, SU Qilong and ZHANG Jing and AN Xiaojing; software, DIAO Kaixuan.; validation, SU Qilong and DIAO Kaixuan.; formal analysis, SU Qilong and DIAO Kaixuan.; resources, REN Guanghui.; data curation, ZHANG Jing and AN Xiaojing.; writing—original draft preparation, SU Qilong; writing—review and editing, REN Guanghui.; project administration, REN Guanghui.; All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data presented in this study are available on request from the corresponding author. The data are not publicly available because of institutional and national data policy restrictions imposed by the ethics committee since the data contain information that could potentially identify study participants. Data are available upon request (contact via rgh@bzmc.edu.cn) for researchers who meet the criteria for access to confidential data (please provide the manuscript title with your inquiry).

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Figures

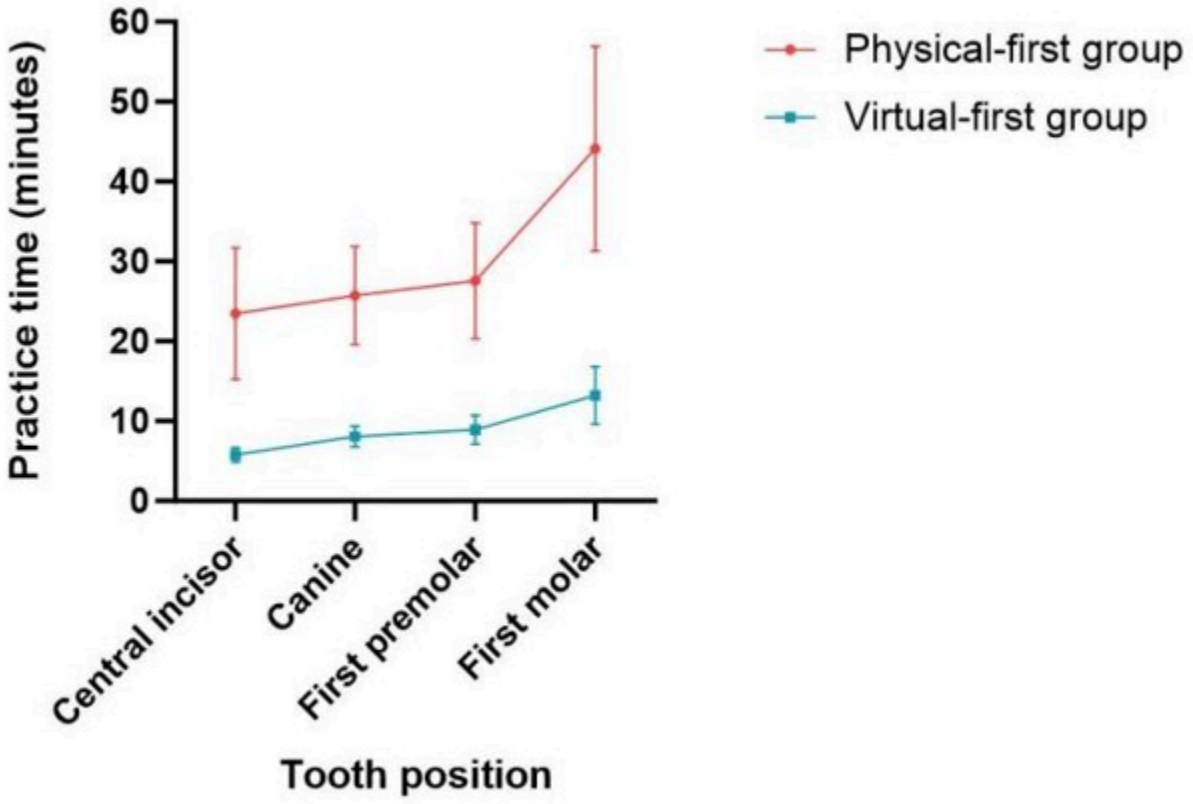


Figure 1

Trend of practice time across tooth positions in the two groups. Data are presented as mean ± SD.

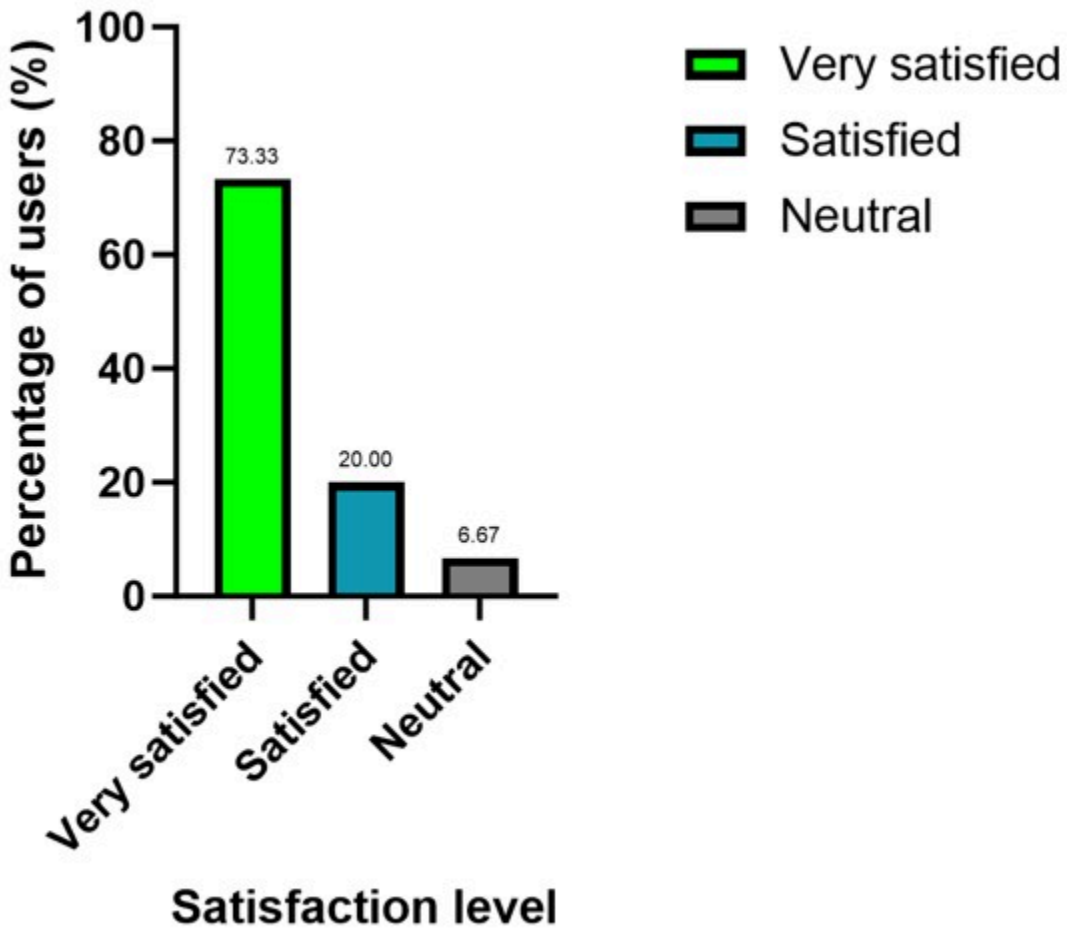


Figure 2

Users' satisfaction with introducing the platform into traditional classrooms.

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