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Revolutionizing Dental Education through Technology: A Comparative Study of Haptic Systems in Tooth Preparation Techniques - A double blinded randomized controlled trial

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ABSTRACT

The evolution of dental education demands innovative tools that bridge the gap between theoretical knowledge and clinical competence. This double-blinded randomized controlled trial evaluated the efficacy of haptic virtual reality (VR) simulators compared to conventional mannequin-based methods in teaching tooth preparation skills to preclinical dental students. Ninety-six first-year Bachelor of Dental Surgery students with no prior clinical experience were randomly assigned to either a conventional training group (Group A) or a haptic VR training group (Group B). Both groups performed mandibular molar crown preparations, assessed on parameters including margin design, occlusal morphology, surface smoothness, undercuts, and total cut volume. Statistical analysis using the Mann–Whitney U test revealed significantly superior performance by the haptic VR group in margin design, undercut formation, and cut volume ($p < 0.001$), while the conventional group performed better in achieving smoother surfaces ($p < 0.001$). No significant difference was observed in occlusal morphology ($p = 0.813$). These findings underscore the potential of haptic VR simulators in enhancing precision and self-directed learning in preclinical settings, while highlighting the complementary value of conventional tactile training. A hybrid educational model integrating both approaches may offer a more comprehensive pathway to clinical readiness.

Keywords: *Haptic simulation, Dental education, Tooth preparation, Virtual reality, Preclinical training*

INTRODUCTION

Dental education has long relied on a structured approach that combines theoretical learning with hands-on practice. The foundation of modern dental education was laid by pioneers like Pierre Fauchard, who emphasized the importance of both scientific knowledge and technical skill development. Over the years, training methodologies have evolved, but the core learning model remains the same: students begin with lectures and foundational coursework, then transition to preclinical training using typodonts (mannequin-based models), before finally advancing to clinical patient care under expert supervision. However, despite its effectiveness, this traditional system has limitations. One of the biggest challenges is the lack of realistic tactile feedback in preclinical training. Plastic typodont teeth do not accurately mimic the hardness of natural teeth or replicate pathological conditions like caries or fractures. Additionally, early psychomotor skill development depends heavily on instructor feedback, leaving little room for self-assessment and independent learning. Furthermore, limited clinical exposure means students may not encounter diverse patient cases until later in their training, which can hinder problem-solving skills and adaptability.

The COVID-19 pandemic brought an abrupt shift to virtual learning across all fields, including dentistry. Social distancing measures and restrictions on in-person training forced dental schools to adopt online learning platforms, video-based instruction, and digital simulations. While these methods ensured continuity of education, they lacked the tactile experience necessary for mastering practical dental skills. This highlighted an urgent need for advanced simulation technologies that could provide realistic training in a virtual setting.

Haptic technology, combined with virtual and augmented reality (VR/AR), is revolutionizing dental education by offering highly immersive, interactive, and realistic training experiences. Unlike traditional mannequins, haptic VR simulators provide real-time sensory feedback, simulating the actual sensations of drilling, cutting, and manipulating tooth structures. These simulators use force feedback mechanisms that replicate the resistance of enamel, dentin, and carious lesions, allowing students to refine their psychomotor skills with greater precision and confidence.

This study aims to compare the effectiveness of conventional tooth preparation methods with haptic VR simulation. By evaluating differences in learning outcomes, psychomotor skill acquisition, and clinical competence, we assess whether haptic technology can enhance preclinical dental training and support remote learning. The results of this study will provide insights into the potential of haptic VR simulators to supplement or even replace traditional preclinical training methods in dental education.

Materials and methods

Study design and Sample size estimation

This is an experimental study that includes two groups: Group A – Students performing preclinical tooth preparations using conventional methods.Group B – Students performing preclinical tooth preparations using haptic virtual reality technology. The study was approved by the university ethical committee (Approval No: SRB/SDC/PROSTHO-2203/23/222). A total of 96 preclinical dental students were selected to participate in the study. The sample size was calculated using G*Power (Version 3.0.10) based on a similar study conducted by Akitaka Hattori et al. The level of significance was set at 0.05, with a power of 90%. Participants were randomly allocated into two groups using block randomization software.

Inclusion and exclusion criteria

The study included first-year Bachelor of Dental Surgery (BDS) students enrolled in the preclinical prosthodontics laboratory and had no prior experience in crown tooth preparation. Only students who voluntarily agreed to participate and provided informed consent were included in the study. Exclusion criteria included students with prior training or clinical experience in tooth preparation. Individuals with motor or neurological disorders that could affect hand dexterity and influence the accuracy of the procedure were also excluded. Additionally, students with visual impairments that could hinder proper assessment of tooth morphology were not eligible. Participants unwilling or unable to complete the full training and assessment protocol were also excluded from the study.

Student demonstration and tooth prepration

Before beginning the tooth preparation exercise, all participants were provided with detailed instructions and demonstrations on mandibular right first molar crown preparation(master reference model), ensuring they understood the correct techniques. To maintain infection control protocols, students were required to wear gloves, masks, and safety glasses. Additionally, they were instructed to maintain an ergonomic posture throughout the procedure to replicate real clinical conditions.

For Group A (Conventional Training), the demonstration was conducted using a conventional mannequin simulator, Clinsim (Morita, Osaka, Japan), with an artificial tooth (A5A-500, Nissin, Kyoto, Japan) and a jaw model (D16FE-500H, GSF MF, Nissin) using a high speed aerator handpiece and diamond cutting burs. Before starting the phantom head simulator was securely positioned, allowing for optimal handpiece control and visibility and mimicking patient positioning.

For Group B (Haptic VR Training), the demonstration was delivered using the haptic simulator from Virteasy Dental (France). Students were guided on calibrating the haptic device, correctly gripping the digital handpiece, and navigating the virtual interface. Special emphasis was placed on understanding the force feedback mechanism, which simulates the resistance of natural tooth structures. Participants were instructed to avoid excessive force and focus on precision and control while using the device.

Following the respective demonstrations, each participant performed tooth preparation on the mandibular right first molar using the same method as demonstrated for their assigned group. A time limit of one hour was allocated for the preparation, during which participants could prepare as many teeth as they wished. At the end of the session, they self-selected their best-prepared tooth for evaluation.

Assessment and Evaluation

The prepared teeth were assessed based on five key parameters: margin design, occlusal morphology, surface smoothness, undercuts, and total cut volume. Evaluations were conducted by two experienced faculty members with over a decade of experience at university level teaching.

To ensure consistency, the assessors used a standardized 10-point Likert scale, where 1 indicated poor quality and 10 indicated excellent quality. Evaluations were performed visually, with assessors comparing each preparation to the reference master preparation model.

Blinding and Reliability Testing

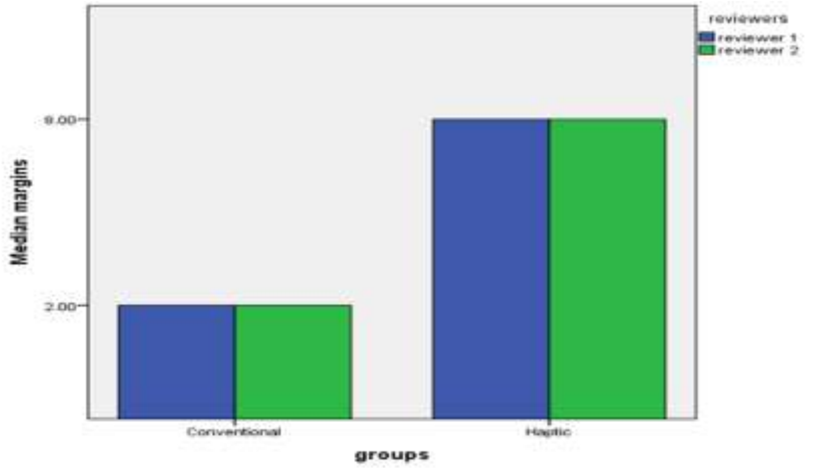
This study followed a single-blind design, where only the statistical assessor was blinded to group assignments. Complete blinding of participants and evaluators was not feasible due to the distinct nature of the training methods. To assess inter-rater reliability, intraclass correlation coefficients (ICCs) were calculated to determine the consistency between the two assessors' scores.

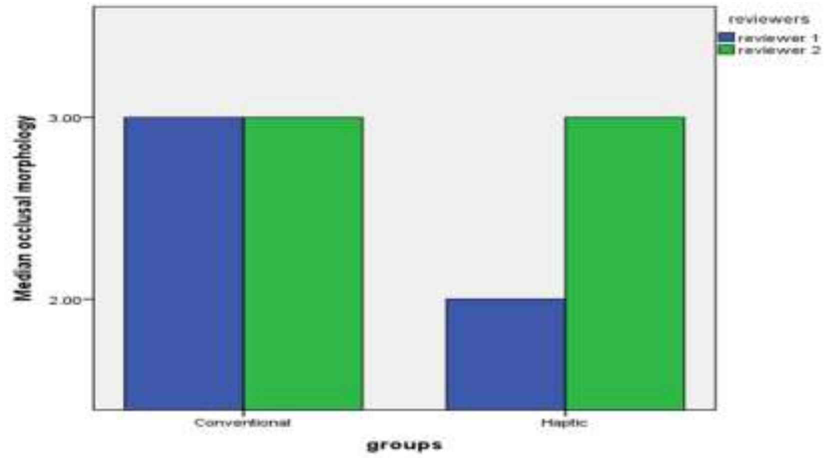
Statistical Analysis

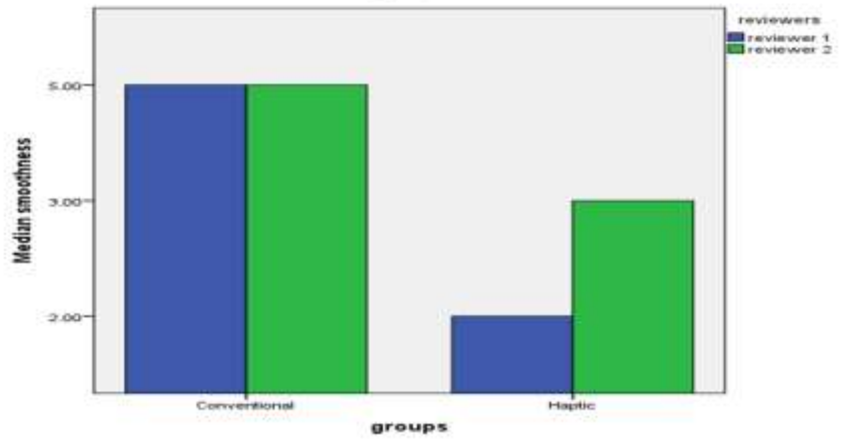
Statistical analysis was performed using Statistical Package for Social Sciences Software (IBM SPSS version 23, USA). The Mann–Whitney U test was used to compare the median scores between the Conventional and Haptic VR training groups. To assess inter-rater reliability, Intraclass Correlation Coefficients (ICCs) were calculated for the evaluators' scores. Descriptive statistics, including median and interquartile range (IQR), were used to summarize the data. A p-value of <0.05 was considered statistically significant.

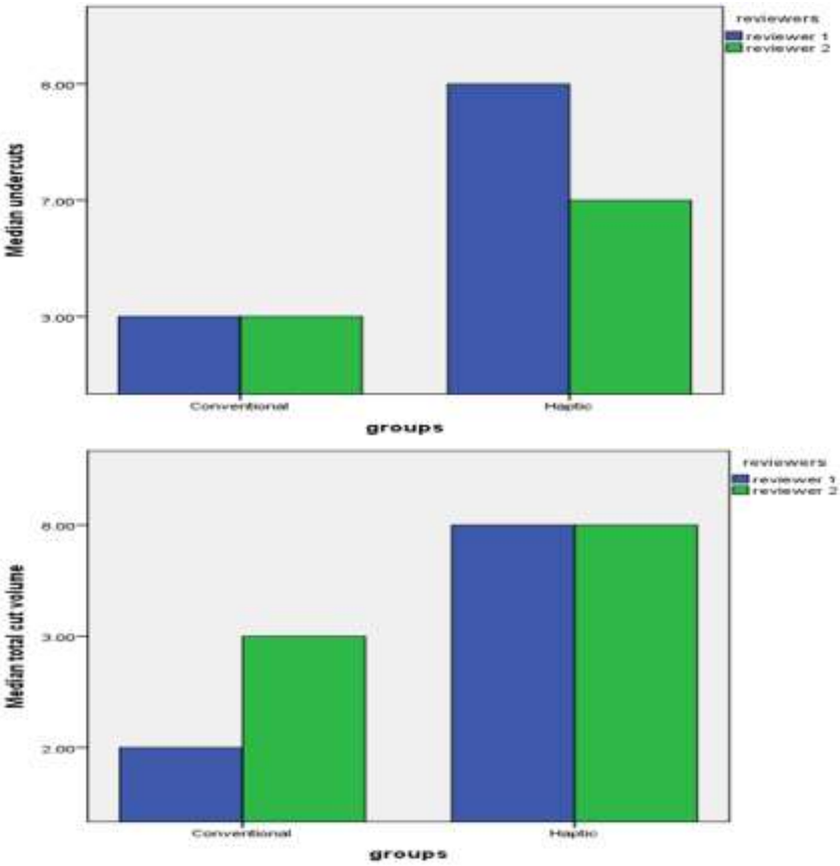
Parameters	Reviewer 1 (Median)		Reviewer 2 (Median)	
	Conventional	Haptic	Conventional	Haptic
Margin design	2	8	2	8
Occlusal morphology	3	2	3	3
Surface smoothness	5	2	5	3
Undercuts	3	8	3	7
Total cut volume	2	8	3	8

Table 1: Median scores given by two reviewers for the parameters of tooth preparation









Graph 1-5 : Median scores given by two reviewers for a) margin design, b) occlusal morphology, c) surface smoothness, d) undercuts and e)total cut volume.

Parameters	Conventional			Haptic			Mann Whitney U Value	p value
	Median	Mean rank	Sum of ranks	Median	Mean rank	Sum of ranks		
Margin design	2	32.17	1383.5	8	54.83	2357.5	437.5	0.000
Occlusal morphology	3	44.12	1897	2	42.88	1844	898	0.813
Surface smoothness	5	59.45	2556	2	27.55	1184.5	238	0.000
Undercuts	3	26.09	1122	8	60.91	2619	176	0.000
Total cut volume	2	25.02	1076	8	61.98	2665	130	0.000

Table 2: Overall scores depicting the significant differences in the parameters between the groups by Mann Whitney U test.

Results

Statistical analysis was conducted using the Mann–Whitney U test to compare the performance of the two groups. The results revealed that the Haptic VR Training group (Group B) achieved significantly higher scores in: Margin design ,Undercuts &Total cut volume ($p < 0.001$)These findings indicate that students trained using haptic VR simulation demonstrated greater precision in margin preparation and better control over undercut formation and material reduction compared to those trained with conventional mannequin-based simulation. However, the Conventional Training group (Group A) outperformed the Haptic VR group in surface smoothness ($p < 0.001$).

This suggests that students practicing on physical typodonts were better able to achieve a uniform and polished preparation compared to those using digital simulation. Regarding occlusal morphology, no statistically significant difference was found between the two groups (p = 0.813), indicating that both training methods were equally effective in helping students replicate the natural contours of the occlusal surface.

Discussion

The findings of this study highlight the effectiveness of haptic virtual reality (VR) training in preclinical dental education, particularly in improving margin design, undercuts, and total cut volume. These results align with previous research emphasizing the need for structured training methods to enhance the precision and consistency of tooth preparation among dental students and novice practitioners. The study by Rosella et al. (2015) supports this concept by demonstrating that a systematic approach to tooth preparation can lead to more predictable results, reducing reliance on manual dexterity and improving overall preparation quality.One of the key challenges in preclinical dental training is achieving standardized tooth preparations while minimizing errors related to operator skill. Rosella et al. noted that students often struggle with maintaining proper occlusal convergence, axial reduction, and finish line accuracy, leading to variations in preparation quality. Similarly, our study found that the Conventional Training group achieved better surface smoothness, likely due to the tactile familiarity of working with physical models. However, the Haptic VR Training group outperformed in precision-related parameters, suggesting that real-time feedback and guided digital simulations help students develop greater accuracy in critical aspects of tooth preparation.

The evaluation methods used in this study also align with the assessment criteria described by Rosella et al. Their study employed a structured grading system based on objective preparation parameters, evaluated by experienced faculty members. Similarly, our study used subjective tutor-based evaluation, emphasizing clinically relevant assessment factors such as occlusal morphology, margin design, and undercuts. The high inter-rater reliability in our study further validates the consistency of tutor-based grading in evaluating preclinical tooth preparations. Another important finding from Rosella et al.'s study is that structured preparation techniques help students control depth and direction of reduction more effectively, reducing common errors such as excessive axial taper or inadequate reduction. The haptic VR simulator in our study provided similar advantages, allowing students to practice multiple times in a controlled, guided environment without the limitations of material availability or instructor supervision. This supports the idea that digital training tools, like haptic VR, can serve as effective supplements to traditional preclinical training methods.

Despite these advantages, time constraints and adaptation to digital tools remain challenges in integrating VR-based training into dental education. While Rosella et al. suggest that a structured manual technique can reduce operator-dependent errors, our findings indicate that haptic feedback technology could further enhance precision by providing real-time guidance and resistance simulation. Future studies should explore hybrid learning approaches, combining haptic VR training with conventional mannequin-based methods to optimize both tactile skill development and precision in tooth preparation.

Conclusion

Haptic virtual reality (VR) training has demonstrated significant advantages in margin design, undercuts, and total cut volume, making it a valuable tool for enhancing precision in tooth preparation. Conventional mannequin-based training, however, remains superior in surface smoothness, highlighting the strengths of tactile learning. Both methods have their own limitations, suggesting that an integrated approach combining the benefits of haptic VR with traditional techniques could provide a more comprehensive training model. The continued refinement of digital simulation technology, alongside structured manual training, has the potential to bridge existing gaps in preclinical dental education and improve overall learning outcomes.

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