European Annals of Dental Sciences
Official Publication of Ankara University, Faculty of Dentistry

EADS, 2023, 50 (3), 143–150

e-ISSN : 2757-6744
doi : 10.52037/eads.2023.0028

Article Received/Accepted : January, 29 2023 / December, 29 2023

REVIEW ARTICLE

The Implication of Virtual Reality Haptic Simulators on Cavity Preparation Proficiency in Dental Preclinical Education: A Systematic Review

Aysenur Oncu *, Berkan Celikten , Emine Odabasi Tezer and Meltem Dartar Öztan

Ankara University, Faculty of Dentistry, Department of Endodontics, Ankara, Turkey

*Corresponding Author; dtaysenuroncu@gmail.com

Abstract

Purpose: An integral component of the dentistry syllabus is preclinical education. The objective of this comprehensive review was to scrutinize the influence of the virtual reality haptic simulator on the enhancement of cavity preparation abilities in the realm of preclinical education.
Materials and Methods: In the context of this investigation, the impact of virtual reality on the enhancement of the preclinical students' cavity preparation proficiency was assessed. In this research, three distinct databases were probed, utilizing Endnote 20 software to replicate, monitor, and handle the selection procedure.
Results: Post the exclusion of replicated records, this study initially yielded a collection of 622 articles. A thorough examination was conducted on all the retrieved records, resulting in the shortlisting of 98 articles for potential eligibility. Papers that failed to satisfy the predetermined eligibility criteria specific to this research were summarily discarded. 24 full-text articles were approved for review.
Conclusions: Incorporating haptic simulators featuring virtual reality into the curriculum could prove advantageous in enhancing students' manual dexterity and enriching their clinical practice.

Key words: Dental education; Haptic simulator; Manual dexterity; Preclinical training; Virtual reality.

Introduction

The pedagogical journey of dental students includes rigorous theoretical and hands-on training throughout their educational tenure. The ethos of dental education is to nurture individuals to become trustworthy, skillful, and effectively practice their chosen profession.[1]Preclinical education represents an integral element, contributing to the evolution of motor skills and facilitating acquisition of pertinent experience within a secure environment. The procedure is conventionally executed in a standard phantom laboratory, utilizing an assortment of instruments on extracted teeth or artificial models. The educational curriculum is designed to augment students' skills in cavity preparation and drilling, applicable in both restorative treatment and endodontics disciplines.[2] Emphasizing the significance of the preclinical years in dentistry academia, students are given the opportunity to hone their abilities to fashion cavities for restorative treatments.[3]

The goal of dental faculties is to enhance both the scientific comprehension and clinical acumen of their students. Presently, the incorporation of emerging technological devices has paved the way for innovative pedagogical strategies in dental education.[4] At this juncture, virtual reality and haptic simulators are gaining notable attention in the field. Visual haptic interactive simulators, offering both visual and tactile feedback, pose as a practical, safe, and consistent alternative to classical dental training methodologies.[5] Dental simulators facilitate the user's ability to interact with and manipulate structures via tactile sensations. Such simulators are integrated with haptic devices, central to which lies an electromechanical framework.[6] Haptic technology entails a tactile feedback mechanism that reproduces the sense of touch by imparting forces, vibrations, or motions to the user via the haptic device.

These haptic devices have found their utility in dental education for procedures like cavity and crown preparation, implant positioning, and pediatric dentistry.[7]Research employing tactile virtual reality simulators for teaching techniques of cavity preparation and dental caries removal have been executed.[8,9]In these research

How to cite: Oncu A, Celikten B, Odabasi Tezer E, Dartar Oztan M. The Implication of Virtual Reality Haptic Simulators on Cavity Preparation Proficiency in Dental Preclinical Education: A Systematic Review EADS. 2023;50(3): 143-150

studies, wherein student performance is gauged, the user is anticipated to generate a variety of shapes and established cavity forms.[10] Within the realms of restorative dentistry and endodontics, the philosophy of cavity preparation has transitioned towards a more conservative technique necessitating heightened precision and skill. In the course of preparation, it is possible to encounter iatrogenic damages which could include the loss of substance along the proximal surfaces of adjacent teeth or over-abundant tooth structure loss, leading to unsuccessful treatments.[3,10]

In order to eliminate these procedural inaccuracies, the objective is to enhance the students' mastery of cavity preparation during preclinical learning periods. In conventional preclinical instruction, students have routinely practiced using a high-speed aerator on extracted or synthetic teeth within phantom heads. Therefore, the modern techniques of learning and the diverse range of educational alternatives call for the serious contemplation of educators. The objective of this systematic review is to assess the influence of the haptic simulator, utilizing virtual reality, in regards to the advancement of cavity training skills within preclinical instruction.

Material and Methods

Study Design

This investigation sought to assess the impact of virtual reality on the enhancement of cavity preparation competencies among preclinical students. In doing so, the review of pertinent experimental studies from authoritative literature was undertaken. To perform an exhaustive search, three independent databases were utilized: PubMed, Web of Science, and Scopus. The Endnote 20 software was employed for the purposes of duplicate detection, record keeping, and managing the overall selection process. The screening of article titles and abstracts was executed by two authors, and those distinctly related to the field of interest were incorporated. The robustness of examiner agreement was quantified through Cohen's kappa statistic (K=0.79). In instances where disagreements arose about the relevance of an article to specific keywords, these were amicably resolved through further deliberations with a third reviewer.

Literature Search Strategy

This systematic review was conducted in adherence to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol. The research question was defined lucidly as: 'Does the incorporation of haptic simulators enhance the proficiency of dental students in cavity preparation during their preclinical years?' The population, intervention, comparison, and outcome (PICO) strategy was used for the structured review question as follows:

- P (Population): Preclinical dental students.
- I (Intervention): The deployment of a haptic simulator for teaching in the preclinical setting.
- C: Traditional preclinical education methods
- O: Improvement of manual dexterity of dental students

An advanced search of the PubMed, Web of Science, and Scopus electronic databases was performed for articles on dental preclinical education published between 2010 and 2022 years. The databases were searched by using the following keywords with the Boolean operators: "haptic simulator", "dental simulation", "preclinical education", "preclinical training", "dental education", "virtual reality".

Eligibility Evaluation

The eligibility criterion was the application of haptic simulators for preclinical education. The target publications were original articles that evaluated simulator training about cavity preparation. The selected studies had to be related to restorative and endodontic treatment.

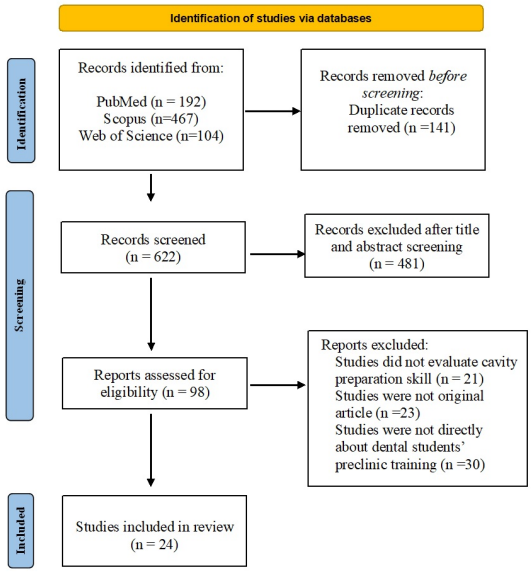

Figure 1. PRISMA flow chart showing the results of the search process.

Inclusion Criteria

The eligibility criteria encompassed articles that were written in English, published within the period of 2010 to 2022, and consisted of full-article downloads.

Exclusion Criteria

Articles that focused on topics including surgical intervention, anesthesia utilization, and crown fabrication were identified as exclusionary criteria. Ultimately, any research that did not assess the ability to prepare cavities was eliminated from the analysis.

Results

The outcome of the search strategy, in adherence with the PRISMA guidelines, is depicted in Figure 1. From the database search, 192 articles were procured from PubMed, 467 articles from Scopus, and 104 articles from Web of Science. Upon the removal of replicated records, the study initially yielded a total of 622 articles. Each record was thoroughly examined, and out of these, 98 articles were deemed suitable for evaluation.

We excluded the articles that did not fulfill our study's eligibility criteria. Subsequently, we sanctioned 24 full-text articles for examination. Table 1 details the attributes of the chosen studies. In our selection, 17 studies from citations 1-30 asserted the positive impact of haptic simulators in preclinical education, specifically improving manual dexterity.[1–30]

There were 5 studies that proposed equivalent efficacy of haptic simulators and traditional phantom training in preclinical education.[1,11,24,25,27]The 2 studies that suggested haptic simulators are not on par with traditional training methods but recommended their usage as an ancillary tool.[18,30]

Table 1. Characteristics of included studies

Author	Article's Title	Number of Participants	Cavity Design	Evaluation Method	Conclusion
Suebnukarn et. al. (2010) [9]	Haptic Virtual Reality for Skill Acquisition in Endodontics	20	endodontic access cavity	Process (speed, force utilization, and bimanual coordination) and outcome variables were determined for assessing skill performance. These values were compared before and after training.	Significant improvements and bimanual coordination were observed in each step of the access cavity in the post-training session.
Gal et al. (2011) [8]	Preliminary Assessment of Faculty and Student Perception of a Haptic Virtual Reality Simulator for Training Dental Manual Dexterity	33	3D geometric shapes	Each participant performed drilling tasks using the simulator and filled out a questionnaire regarding the simulator and potential ways of using it in dental education.	The results show that experienced dental faculty members as well as advanced dental students found that the simulator could provide significant potential benefits in the teaching and self-learning of manual dental skills.
Urbankova et al. (2013) [10]	A Complex Haptic Exercise to Predict Preclinical Operative Dentistry Performance: A Retrospective Study	39	different shapes, e.g., straight lines, circle, D shaped circle	The examination scores were determined by four clinical faculty members who were calibrated and masked with respect to student identity and haptic scores.	The number of failures during a single session on a complex haptic exercise was found to be a significant predictor of examination performance in the preclinical setting.
Gottlieb et al. (2011) [17]	Faculty Impressions of Dental Students' Performance with and Without Virtual Reality Simulation	202	simple and complex cavity shapes	The survey was administered to educators 3 times. Evaluation of the faculty's perceptions of Virtual Reality Simulation and traditional training students' abilities with a questionnaire.	Virtual reality simulation training gives students an advantage in the clinic.
Suebnukarn et al. (2011) [25]	Access Cavity Preparation Training Using Haptic Virtual Reality and Microcomputed Tomography Tooth Models	32	endodontic access cavity	The pre-training and post-training endodontic access cavities of the two groups who received Virtual Reality Simulation training or phantom head training were evaluated in terms of procedural errors by an educator blinded to the study.	Virtual reality simulators and conventional phantom heads have a similar effect in preclinical education in reducing procedural errors in endodontic access cavities.
Urbankova et al. (2011) [26]	The Use of Haptics to Predict Preclinic Operative Dentistry Performance and Perceptual Ability	39	straight line, circle, and mirror line	Haptic exercise outcomes for accuracy, time, and success rate were measured using commercially available computer software.	These results suggest that haptic devices have a potential role in predicting performance in preclinical dental education.
Yamaguchi et al. (2013) [28]	The Usefulness of a Haptic Virtual Reality Simulator with Repetitive Training to Teach Caries Removal and Periodontal Pocket Probing Skills	7	occlusal cavity	Performance was scored based on the volume of the cut region, the number of instances of handpiece overload, and total cutting time.	The simulator was effective at teaching hand skills for caries removal within the short-term evaluation.
Koo et. al. (2015) [18]	An Initial Assessment of Haptics in Preclinical Operative Dentistry Training	34	three-dimensional geometric shapes	The questionnaire survey was given to the experimental group to assess the subjective evaluation of the haptic simulation exercise in their preclinical training.	The haptic exercises with the IDEA manual dexterity module were not superior in improving the dexterity of students for tooth cavity preparations in preclinical laboratory sessions in this pilot project, except for the management of the adjacent tooth.
Al-Saud et al. (2016) [1]	Feedback and Motor Skill Acquisition Using a Haptic Dental Simulator	63	five different geometric shapes	Participants completed four tasks during which feedback was given according to group allocation as well as two skills transfer tests. Skill retention was examined immediately after training, at 1 week, and at 1-month post-test.	The study indicates that the acquisition and retention of basic dental motor skills in novice trainees is best optimized through a combination of instructor and visual display (VR)-driven feedback.
Bakker et. al. (2016) [12]	Effect of Students' Determination of Testing Time on Their Test Performance	231	various models with geometrical figures	After the training, the students performed a test. The results of the test were stored in a database.	Increasing the application of automatic feedback in this training environment would enable students to increase their independent learning experiences.

Mirghani et. al. (2016) [20]	Capturing Differences in Dental Training Using a Virtual Reality Simulator	377	cross-shape	Real-time feedback on performance was presented on a computer monitor attached to the device throughout the task. The feedback information included a percentage score for each of the target error scores and drill time.	The present study suggests that research on this topic is highly justified and could lead to a step change in dental education practice.
de Boer et al. (2017) [13]	The Effect of Force Feedback in a Virtual Learning Environment on the Performance and Satisfaction of Dental Students	101	cross shape	The performance and satisfaction of students working with virtual reality training were evaluated with a questionnaire.	The results suggest that Force Feedback is important for performance in a Virtual Learning Environment and essential for satisfaction.
Llena et.al. (2017) [19]	Implementation of Augmented Reality in Operative Dentistry Learning	41	Black Class I and Class II cavities	Questionnaires were designed to evaluate knowledge and skills, with the administration of a satisfaction questionnaire for those using Augmented Reality. The degree of compliance with the standards in cavity design was assessed.	The present study's findings revealed that only some of the studied skills were better in the experimental group. The Augmented Reality techniques favored gaining knowledge and skills and were regarded as useful tool by the students.
Shahriari-Rad et al. (2017) [24]	Clinical Skills Acquisition: Rethinking Assessment Using a Virtual Haptic Simulator	140	caries removal	Pre- and post-psychometric tests were used to measure their spatial reasoning and manipulation skills.	The use of both traditional and virtual reality simulation models of training resulted in an improvement in certain psychomotor skills which are essential for students' clinical practice.
Dwisaptarini et al. (2018) [15]	Effectiveness of the Multilayered Caries Model and visuo-tactile Virtual Reality Simulator for Minimally Invasive Caries Removal: A Randomized Controlled Trial	32	minimally invasive caries removal	The main outcome measure in both groups was performance scores assessed by an expert blinded to trainee and training status. The secondary outcome measures were tooth mass loss and task completion time.	Training on the micro-CT multilayered caries model with the visuo-tactile virtual reality simulator and the conventional extracted tooth had equivalent effects on improving the performance of minimally invasive caries removal.
Ria et.al. (2018) [22]	A Scoring System for Assessing Learning Progression of Dental Students' Clinical Skills Using Haptic Virtual Workstations	101	removing carious lesions	On-screen results were photographed and submitted by the students to the tutors. A scoring system named the Accuracy of Caries Excavation (ACE) score was devised to score these results.	Using the HapTEL system in a first-year BDS curriculum improved the students' performance of simulated cavity preparation after practicing over two sessions
de Boer et al. (2019) [14]	The Effect of Variations in Force Feedback in a Virtual Reality Environment on the Performance and Satisfaction of Dental Students	126	cross-figure preparation, donut preparation, and sloped channel preparation	The test consisted of drilling with the standard Force Feedback and an altered level of Force Feedback to evaluate the effect on performance. After the test, the participants completed a questionnaire.	This study showed that novice students can acquire a manual dexterity skill at one level of Force Feedback and transfer this skill to another level of Force Feedback in which they have never previously practiced.
Aliaga et al. (2020) [11]	Preclinical assessment methodology using a dental simulator during dental students' first and third years	82	preparation of three cavities with geometric forms (i.e., bar, circle, and cross)	The parameters measured by the Simodont were used as predictors of the methacrylate block evaluation's results, performed by a professor.	Both methodologies can detect manual skill improvement in dental students.
Murbay et al. (2020) [21]	Evaluation of the Introduction of a Dental Virtual Simulator on the Performance of Undergraduate Dental Students in the Preclinical Operative Dentistry Course	32	SISTA Classification—Site 1 cavity preparation on molar teeth	Preparations were evaluated using manual and digital methods by three evaluators blinded to the study.	Virtual reality was found to be effective in the improvement of cavity preparations of undergraduate dentistry students.
Vincent et al. (2020) [27]	Contribution of Haptic Simulation to Analogic Training Environments in Restorative Dentistry	88	Black's Class 2 cavity preparation on #46	Comparison of objective parameters obtained from the haptic simulator system with subjective parameters evaluated by educators blinded to the study.	Virtual reality and traditional learning achievements were found similar.

Zafar et al. (2020) [29]	Virtual Reality as a novel educational tool in preclinical pediatric dentistry training: Students' perceptions	100	pulpotomy cavity	The perceptions of the students who completed the phantom head laboratory training and the training in the Simodont dental trainer were evaluated with a questionnaire.	The study suggests that Simodont could be used as an adjunct in training dental students for preclinical pediatric dentistry restorative exercises.
Farag et.al. (2021) [16]	Impact of the Haptic Virtual Reality Simulator on Dental Students' Psychomotor Skills in Preclinical Operative Dentistry	21	Class I cavity preparation	The prepared cavities before and after Haptic Virtual Reality Simulator training for each student were used as an assessment tool for the students' psychomotor skills. Two evaluators carried out the assessments.	There was an overall improved performance in the psychomotor skills evidenced by improved cavity preparation scores and cavity design features and less time for cavity preparation after Haptic Virtual Reality Simulator training.
Ziane-Casenave et.al.(2021) [30]	Influence of practical and clinical experience on dexterity performance measured using haptic virtual reality simulator	56	occlusal amalgam cavity	The dental students and recent graduates completed a questionnaire to gather their opinions about their first hands-on experience with a haptic simulator.	The questionnaire indicated a tendency for dental operators to consider the simulator as a complement to their learning and not a substitute for traditional methods.
Rodrigues et al. (2022) [23]	Usability, acceptance, and educational usefulness study of a new haptic operative dentistry virtual reality simulator	13	Class I or II cavity preparation	Participant feedback was obtained through a structured questionnaire or post-experiment interview debriefing, regarding the limitations and benefits of the proposed interaction techniques.	DENTIFY presented significant usability and acceptance from trained dentists. This tool showed to have teaching and learning potential in operative dentistry.

Figure 2. Equipment of haptic simulator (Simodont dental trainer, Nissin Dental Products, Nieuw-Vennep, Netherlands)

Discussion

In the domain of operative dentistry, the utility of phantom head simulators has been appreciated for an extensive period, chiefly in the context of preclinical training to hone delicate psychomotor skills prior to engaging with actual patients.[16] Phantom heads equipped with synthetic or authentic teeth have offered the requisite simulation for assimilating various treatment protocols necessary for clinical practice.[31] Recently, haptic simulators are witnessing a rising prevalence in the structure of preclinical education.[32] The primary objective of this systematic review was to dig deep into the value addition by haptic simulators in the field of dental preclinical education.

The incorporation of virtual reality simulation has noticeable growth, attributed to its ability to facilitate direct scrutiny, minimize the consumption of resources, and enable the standardization and repetition of procedures.[33] Specifically, haptic simulation training offers potential benefits to dental students by providing a safe environment to engage in skill acquisitions effectively before gaining exposure to patient care in dentistry.[31,34] Dental training simulators are a result of the adaptation of pre-existing technologies, most notably from the medical and aviation fields.[35] Haptic simulators have a lot of equipment e.g. instruments such as touch screens, dental handpieces, space mouses, dental mirrors, and speed pedals are typically part of the equipment suite.(Figure 2) Key industry players in this realm include DentSim™, PerioSim©, Simodont®, VirTeaSy Dental©, DENTIFY, and IDEA.[30,36] Multiple research studies have rigorously evaluated the efficacy of these devices.[11,37,38]

Successful execution of treatment techniques in operative dentistry hinges significantly on the practitioner's manual dexterity.[39] Hence, a significant portion of undergraduate edification is targeted at enhancing the psychomotor clinical aptitude of pupils.[40] The frequently encountered dental procedures entail endodontic and restorative cavity preparations that necessitate a meticulous drill operation of a tooth demanding precise hand-eye coordination coupled with depth perception.[3] The protocol of creating dental cavities on teeth involves adherence to certain criteria; these are the elimination of caries, accounting for substance loss within the tooth, reinstitution of the tooth's anatomical configuration, and delivering function and aesthetics.[41] It is essential for pupils to conduct cavity preparations cognizant of these factors. Nonetheless, initial attempts to master this by the students may prove to be challenging.[27,42] Haptic simulators offer an abundance of practice attempts and display a variety of tasks and scenarios for training purposes, aimed at boosting the manual dexterity of students.[43]

The results of qualitative synthesis suggest that the majority of studies confirm the advantageous impact of haptic simulators on manual dexterity. Virtual reality training evaluation criteria varied across the studies detailed in Table 1.[1–30] Unfortunately, quantitative results for comparison are absent from the studies chosen for this systematic review on the subject. Therefore, it was not possible to conduct a Meta-Analysis. The studies included in this review utilized various cavity shapes in their virtual reality training programs. Notably, the study participants, across all included studies, were dental students of diversified academic levels.

The conclusion drawn from 17 studies indicates a significant contribution of haptic simulators to the enhancement of manual dexterity in the process of cavity preparation. Table 1 illustrates the various methods employed in these studies, which employed parameters such as divergent participant counts, cavity formations, and haptic simulator devices. Even with variations in methodology and appraisal scales, research repeatedly underscores the value of haptic simulators in dental education. Contrarily, it was noted in two pieces of research that the efficacy of haptic simulators was eclipsed by traditional teaching methods in relation to cavity formation capability.[18,30] Furthermore, these studies utilized dissimilar haptic simulator devices, positing that they did not offer any additional benefit above traditional learning methods.

Therefore, Ziane-Casenave et al. emphasize the fact that the application of haptic simulators warrants refinement especially in areas such as authenticity, feedback mechanism, and evaluation.[30] The assessment of student accomplishments should be considered a direct result of simulation training.[22] It is crucial to pinpoint appropriate variables capable of quantitatively demonstrating a learner's level of proficiency or skill attainment, in conjunction with the development of objective scoring criteria that foster the establishment of logical educational structures.[9] Designing studies involving large cohorts of participants is a practical approach for outlining learning progression over an extended period.[22]

Haptic simulators, however, present distinct limitations regarding both their hardware and software components. During dental procedures such as cavity preparation, the force feedback from different oral tissues is a perceptual cue relied upon by practitioners. In the context of dental training, the precision of force feedback within the simulator is regarded as a vital component. In contrast, practitioners must also ensure the preservation of soft tissues when employing high-velocity aerators. The simulation of soft tissue deformation such as tongue, gingiva, lip, and cheek need to be simulated realistically. However, the simulation of these tissues has not yet been adequately achieved.[44]

Financial infrastructure is required to include simulator training in the curriculum. Notably, institutions must provide adequate funding for initial payment costs. In addition, faculties need to have training supervisory staff, as well as ongoing funding allocations for maintenance and software updates of virtual reality simulators.[31]

Given the need to visualize and implement curriculum content in clinical departments, virtual reality simulation can be used for dental education at different levels.[45] The literature reveals that the employment of haptic simulators plays a pivotal role in enhancing learning within the preclinical curriculum.[20,46,47]

Conclusion

Insights gleaned from this systematic review reveal that leveraging virtual reality haptic simulators can significantly buttress student's skills in cavity preparation and learning management during preclinical instruction. A majority of these studies underscore the inherent value of such simulators in honing manual dexterity, a requisite skill in the realms of endodontics and restorative dentistry. In these investigations, the emulation of the different types of teeth and cavities has delivered encouraging results, mitigat-

ing the challenges students encounter when transitioning from a preclinical to a clinical environment. There is a strong case to integrate simulation-based practice into the standard dental education curriculum, given the availability of the appropriate infrastructure.

Author Contributions

BC and MDO designed the study. AO and EOT performed methodology. AO and EOT wrote- reviewed and edited the manuscript. BC and MDO contributed to all parts of the manuscript and approved the manuscript.

Conflict of Interest

The authors declare no competing interests.

Authors' ORCID(s)

A.O. 0000-0002-3130-0669
B.C. 0000-0001-5645-5029
E.O.T. 0000-0003-3669-5062
M.D.Ö 0000-0002-1693-0355

References

1. Al-Saud LM, Mushtaq F, Allsop MJ, Culmer PC, Mirghani I, Yates E, et al. Feedback and motor skill acquisition using a haptic dental simulator. Eur J Dent Educ. 2017;21(4):240–247. doi:10.1111/eje.12214.
2. González Bravo L, Fernández Sagredo M, Torres Martínez P, Barrios Penna C, Fonseca Molina J, Stanciu ID, et al. Psychometric analysis of a measure of acceptance of new technologies (UTAUT), applied to the use of haptic virtual simulators in dental students. Eur J Dent Educ. 2020;24(4):706–714. doi:10.1111/eje.12559.
3. Al-Saud LM. The utility of haptic simulation in early restorative dental training: A scoping review. J Dent Educ. 2021;85(5):704–721. doi:10.1002/jdd.12518.
4. Park JC, Kwon HE, Chung CW. Innovative digital tools for new trends in teaching and assessment methods in medical and dental education. J Educ Eval Health Prof. 2021;18:13. doi:10.3352/jeehp.2021.18.13.
5. Lin Y, Wang X, Wu F, Chen X, Wang C, Shen G. Development and validation of a surgical training simulator with haptic feedback for learning bone-sawing skill. J Biomed Inform. 2014;48:122–9. doi:10.1016/j.jbi.2013.12.010.
6. Escobar-Castillejos D, Noguez J, Neri L, Magana A, Benes B. A Review of Simulators with Haptic Devices for Medical Training. J Med Syst. 2016;40(4):104. doi:10.1007/s10916-016-0459-8.
7. Wu W, Cen Y, Hong Y, Keeling A, Khambay B. A pilot study to assess the feasibility and accuracy of using haptic technology to occlude digital dental models. J Dent. 2016;46:54–60. doi:10.1016/j.jdent.2016.01.004.
8. Gal GB, Weiss EI, Gafni N, Ziv A. Preliminary assessment of faculty and student perception of a haptic virtual reality simulator for training dental manual dexterity. J Dent Educ. 2011;75(4):496–504.
9. Suebnukarn S, Haddawy P, Rhienmora P, Gajananan K. Haptic virtual reality for skill acquisition in endodontics. J Endod. 2010;36(1):53–5. doi:10.1016/j.joen.2009.09.020.
10. Urbankova A, Eber M, Engebretson SP. A complex haptic exercise to predict preclinical operative dentistry performance: a retrospective study. J Dent Educ. 2013;77(11):1443–50.
11. Aliaga I, Pedrera-Canal M, Vera V, Rico Martín S, Garcia Barbero E, Leal-Hernández O, et al. Preclinical assessment methodology using a dental simulator during dental students' first and third years. J Oral Sci. 2020;62(1):119–121. doi:10.2334/josnusd.18-0424.
12. Bakker DR, Deng DM, Wesselink PR, Vervoorn JM. Effect of students' determination of testing time on their test performance. Eur J Dent Educ. 2017;21(3):137–141. doi:10.1111/eje.12192.
13. de Boer IR, Lagerweij MD, de Vries MW, Wesselink PR, Vervoorn JM. The Effect of Force Feedback in a Virtual Learning Environment on the Performance and Satisfaction of Dental Students. Simul Healthc. 2017;12(2):83–90. doi:10.1097/sih.0000000000000208.
14. de Boer IR, Lagerweij MD, Wesselink PR, Vervoorn JM. The Effect of Variations in Force Feedback in a Virtual Reality Environment on the Performance and Satisfaction of Dental Students. Simul Healthc. 2019;14(3):169–174. doi:10.1097/sih.0000000000000370.
15. Dwisaptarini AP, Suebnukarn S, Rhienmora P, Haddawy P, Koontongkaew S. Effectiveness of the Multilayered Caries Model and Visuo-tactile Virtual Reality Simulator for Minimally Invasive Caries Removal: A Randomized Controlled Trial. Oper Dent. 2018;43(3):E110–e118. doi:10.2341/17-083-c.
16. Farag A, Hashem D. Impact of the Haptic Virtual Reality Simulator on Dental Students' Psychomotor Skills in Preclinical Operative Dentistry. Clin Pract. 2021;12(1):17–26. doi:10.3390/clinpract12010003.
17. Gottlieb R, Lanning SK, Gunsolley JC, Buchanan JA. Faculty impressions of dental students' performance with and without virtual reality simulation. J Dent Educ. 2011;75(11):1443–51.
18. Koo S, Kim A, Donoff RB, Karimbux NY. An initial assessment of haptics in preclinical operative dentistry training. J Investig Clin Dent. 2015;6(1):69–76. doi:10.1111/jicd.12065.
19. Llena C, Folguera S, Forner L, Rodríguez-Lozano FJ. Implementation of augmented reality in operative dentistry learning. Eur J Dent Educ. 2018;22(1):e122–e130. doi:10.1111/eje.12269.
20. Mirghani I, Mushtaq F, Allsop MJ, Al-Saud LM, Tickhill N, Potter C, et al. Capturing differences in dental training using a virtual reality simulator. Eur J Dent Educ. 2018;22(1):67–71. doi:10.1111/eje.12245.
21. Murbay S, Neelakantan P, Chang JWW, Yeung S. 'Evaluation of the introduction of a dental virtual simulator on the performance of undergraduate dental students in the pre-clinical operative dentistry course'. Eur J Dent Educ. 2020;24(1):5–16. doi:10.1111/eje.12453.
22. Ria S, Cox MJ, Quinn BF, San Diego JP, Bakir A, Woolford MJ. A Scoring System for Assessing Learning Progression of Dental Students' Clinical Skills Using Haptic Virtual Workstations. J Dent Educ. 2018;82(3):277–285. doi:10.21815/jde.018.028.
23. Rodrigues P, Esteves A, Botelho J, Machado V, Zagalo C, Zorzal ER, et al. Usability, acceptance, and educational usefulness study of a new haptic operative dentistry virtual reality simulator. Comput Methods Programs Biomed. 2022;221:106831. doi:10.1016/j.cmpb.2022.106831.
24. Shahriari-Rad A, Cox M, Woolford M. Clinical Skills Acquisition: Rethinking Assessment Using a Virtual Haptic Simulator. Technology, Knowledge and Learning. 2017;22(2):185–197. doi:10.1007/s10758-017-9308-1.
25. Suebnukarn S, Hataidechadusadee R, Suwannasri N, Suprasert N, Rhienmora P, Haddawy P. Access cavity preparation training using haptic virtual reality and microcomputed tomography tooth models. Int Endod J. 2011;44(11):983–9. doi:10.1111/j.1365-2591.2011.01899.x.
26. Urbankova A, Engebretson SP. The use of haptics to predict preclinic operative dentistry performance and perceptual ability. J Dent Educ. 2011;75(12):1548–57.
27. Vincent M, Joseph D, Amory C, Paoli N, Ambrosini P, Mortier E, et al. Contribution of Haptic Simulation to Analogic

Training Environment in Restorative Dentistry. J Dent Educ. 2020;84(3):367–376. doi:10.21815/jde.019.187.
28. Yamaguchi S, Yoshida Y, Noborio H, Murakami S, Imazato S. The usefulness of a haptic virtual reality simulator with repetitive training to teach caries removal and periodontal pocket probing skills. Dent Mater J. 2013;32(5):847–52. doi:10.4012/dmj.2013-174.
29. Zafar S, Lai Y, Sexton C, Siddiqi A. Virtual Reality as a novel educational tool in pre-clinical paediatric dentistry training: Students' perceptions. Int J Paediatr Dent. 2020;30(6):791–797. doi:10.1111/ipd.12648.
30. Ziane-Casenave S, Mauroux M, Devillard R, Kérourédan O. Influence of practical and clinical experience on dexterity performance measured using haptic virtual reality simulator. Eur J Dent Educ. 2022;26(4):838–848. doi:10.1111/eje.12767.
31. Perry S, Burrow MF, Leung WK, Bridges SM. Simulation and curriculum design: a global survey in dental education. Aust Dent J. 2017;62(4):453–463. doi:10.1111/adj.12522.
32. Al-Saud LM, Mushtaq F, Mann RP, Mirghani I, Balkhoyor A, Harris R, et al. Early assessment with a virtual reality haptic simulator predicts performance in clinical practice. BMJ Simul Technol Enhanc Learn. 2020;6(5):274–278. doi:10.1136/bmjstel-2018-000420.
33. Abich J, Parker J, Murphy JS, Eudy M. A review of the evidence for training effectiveness with virtual reality technology. Virtual Real. 2021;25(4):919–933. doi:10.1007/s10055-020-00498-8.
34. McAlpin E, Levine M, Plass JL. Comparing two whole task patient simulations for two different dental education topics. Learning and Instruction. 2023;83:101690. doi:https://doi.org/10.1016/j.learninstruc.2022.101690.
35. Dut M, Amariei C, Bogdan CM, Popovici DM, Ionescu NS, Nucă C. An Overview of Virtual and Augmented Reality in Dental Education. oral health and dental management. 2011;2011:0–0.
36. Roy E, Bakr MM, George R. The need for virtual reality simulators in dental education: A review. Saudi Dent J. 2017;29(2):41–47. doi:10.1016/j.sdentj.2017.02.001.
37. Ben-Gal G, Weiss EI, Gafni N, Ziv A. Testing manual dexterity using a virtual reality simulator: reliability and validity. Eur J Dent Educ. 2013;17(3):138–42. doi:10.1111/eje.12023.
38. Chen ML, Su ZY, Wu TY, Shieh TY, Chiang CH. Influence of dentistry students' e-Learning satisfaction: a questionnaire survey. J Med Syst. 2011;35(6):1595–603. doi:10.1007/s10916-010-9435-x.
39. Bayne SC. Correlation of clinical performance with 'in vitro tests' of restorative dental materials that use polymer-based matrices. Dent Mater. 2012;28(1):52–71. doi:10.1016/j.dental.2011.08.594.
40. Nassar HM, Tekian A. Computer simulation and virtual reality in undergraduate operative and restorative dental education: A critical review. J Dent Educ. 2020;84(7):812–829. doi:10.1002/jdd.12138.
41. McComb D. Systematic review of conservative operative caries management strategies. J Dent Educ. 2001;65(10):1154–61.
42. Imran E, Adanir N, Khurshid Z. Significance of Haptic and Virtual Reality Simulation (VRS) in the Dental Education: A Review of Literature. Applied Sciences. 2021;11(21):10196.
43. Coro-Montanet G, Pardo Monedero MJ, Sánchez Ituarte J, de la Hoz Calvo A. Train Strategies for Haptic and 3D Simulators to Improve the Learning Process in Dentistry Students. Int J Environ Res Public Health. 2022;19(7). doi:10.3390/ijerph19074081.
44. Li Y, Ye H, Ye F, Liu Y, Lv L, Zhang P, et al. The Current Situation and Future Prospects of Simulators in Dental Education. J Med Internet Res. 2021;23(4):e23635. doi:10.2196/23635.
45. Soltanimehr E, Bahrampour E, Imani MM, Rahimi F, Almasi B, Moattari M. Effect of virtual versus traditional education on theoretical knowledge and reporting skills of dental students in radiographic interpretation of bony lesions of the jaw. BMC Med Educ. 2019;19(1):233. doi:10.1186/s12909-019-1649-0.
46. Rhienmora P, Haddawy P, Khanal P, Suebnukarn S, Dailey MN. A virtual reality simulator for teaching and evaluating dental procedures. Methods Inf Med. 2010;49(4):396–405. doi:10.3414/me9310.
47. Zafar S, Siddiqi A, Yasir M, Zachar JJ. Pedagogical development in local anaesthetic training in paediatric dentistry using virtual reality simulator. Eur Arch Paediatr Dent. 2021;22(4):667–674. doi:10.1007/s40368-021-00604-7.